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DISPOSAL OF SOLID RADIOACTIVE WASTES IN BEDDED SALT DEPOSITS

Report by the

Committee on Radioactive Waste Management

National Academy of Sciences - National Research Council

Washington, D.C.

November 1970

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Report by the

COMMITTEE ON RADIOACTIVE WASTE MANAGEMENT

Sponsored by the

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SUMMARY AND CONCLUSIONS

At the request of the Atomic Energy Commission (AEC), the Committee on Radioactive Waste Management (CRWM) of the National Academy of Sciences - National Research Council has examined the technical feasibility of the burial of solid radioactive wastes in bedded salt deposits. This method of waste management was originally suggested in 1957[1] by an earlier Academy advisory committee and has been under continuous study and development since that time by the Oak Ridge National Laboratory. In June 1970, the AEC announced its intention to initiate a demonstration project to provide technical data and experience on operational methods and costs of long-term storage of solidified wastes from the processing of spent nuclear power fuels. A site near Lyons, Kansas, has been selected tentatively as the location of the demonstration project for a salt mine repository.

To assist in the evaluation of the AEC plans, the CRWM convened a Panel on Disposal in Salt Mines. Based on the recommendations of the panel, the Committee reached the following conclusions:

1. The use of bedded salt for the disposal of radioactive wastes is satisfactory. In addition, it is the safest choice now available, provided the wastes are in an appropriate form and the salt beds meet the necessary design and geological criteria.

Committee on Radioactive Waste Management

John C. Frye, Chairman, Illinois State Geological Survey

W. Kenneth Davis, Bechtel Corporation

Peter T. Flawn, University of Texas at Austin

Clark Goodman, University of Houston

Jack E. McKee, California Institute of Technology

Herbert M. Parker, Battelle Memorial Institute, Northwest Laboratories

John F. Reed, University of Wisconsin-Green Bay

John H. Rust, University of Chicago

Howard H. Seliger, The Johns Hopkins University

F. H. Spedding, Ames Laboratory, Iowa State University

Clarke Williams, Nassau-Suffolk Regional Planning Board

John A. Erlewine, Liaison, U. S. Atomic Energy Commission

Cyrus Klingsberg, Technical Secretary, National Academy of Sciences

Panel on Disposal in Salt Mines

John H. Rust, Chairman, University of Chicago

John C. Frye, Illinois State Geological Survey

Earnest F. Gloyna, University of Texas

William W. Hambleton, Kansas State Geological Survey

Frank Parker, Vanderbilt University

C. V. Theis, U. S. Geological Survey

Cyrus Klingsberg, Technical Secretary, National Academy of Sciences

2. The site near Lyons, Kansas, selected by the AEC is satisfactory, subject to the development of certain additional confirmatory data and evaluation. Initial disposal will be for low level solid waste material contaminated with plutonium and other long-lived transuranium nuclides. Subsequent disposal will include highly radioactive, high temperature, solidified wastes.

BACKGROUND INFORMATION*

In 1957, an advisory committee of the National Academy of Sciences - National Research Council recommended that high-level radioactive wastes be buried in excavations in bedded salt deposits.[1] Laboratory and field studies on the feasibility of such disposal of high-level liquid waste were conducted by the Oak Ridge National Laboratory (ORNL) during 1957-61.[2] The results were reviewed by another NAS - NRC committee in 1961.[3] That committee recommended that more extensive studies be directed toward solidified wastes and such studies were conducted by the ONRL for the AEC between 1963-67 under the project name of Salt Vault.[4] In 1966,[5] a subsequent NAS - NRC committee continued the advocacy of burial of radioactive wastes in bedded salt. The ORNL, after a favorable estimate of the feasibility of such an undertaking (1968-69),[6] developed a conceptual design during 1969-70 for a prototype facility to bury highly radioactive, high-temperature, solidified waste from the chemical processing of spent fuel elements in bedded salt. In 1970, the

*Additional information is included in the Appendix.

concept was expanded to include the burial of low-thermal alpha waste, i.e., materials contaminated with plutonium and other transuranium nuclides.

In 1968, the Committee on Radioactive Waste Management (CRWM) was established by the NAS - NRC at the request of the AEC. As part of its charge to advise the AEC concerning its long-range radioactive waste management plans, the CRWM responded to a specific request to evaluate the feasibility of disposal of solidified radioactive waste in bedded salt in the light of present technology. On October 17-18, 1968, the Committee met at Oak Ridge to review the ORNL programs on waste solidification and disposal.[7] Later, the Committee formed the Panel on Disposal in Salt Mines, which first met at the ORNL on May 21-22, 1970, to hear a presentation on the burial of radioactive wastes in bedded salt and to make recommendations to the CRWM. The geological data and preliminary engineering design information covered the burial of solidified, high-heat emitting waste as well as the burial of alpha waste.

Advantages of Salt Mine Burial

The advantages of burying radioactive wastes in a bedded salt mine are as follows:

1. A highly radioactive source separated from the environment by a thickness of good-quality bedded salt in an area of tectonic stability is effectively isolated from that environment for at least 1,000 years and probably for significantly longer.

2. Bedded salt has a high compressive strength but flows plastically at relatively low temperatures and pressures. This will relieve stress concentrations produced by the mining operation or by the heat generated by the radioactive waste.

3. Fractures that might develop in bedded salt are "self-healing." This is indicated in part by the absence of solution cavities in the rock salt that has been studied.

4. The natural plasticity of the salt at the temperature imposed by the highly radioactive waste will effectively seal the remnants of the containers in cells of crystalline salt. Should man, for a now unforeseen reason, have to remove the buried radioactive waste, it could be accomplished with specialized mining equipment, albeit with considerable difficulty and effort.

5. Bedded salt permits the dissipation of larger quantities of heat than is possible in other types of rock.

6. Rock salt is approximately equal to concrete for gamma-ray shielding. Experimental radiation exposure has caused very little detectable radiolytic change in rock salt.

7. The loss of our salt resources would be negligible. There is a great abundance of bedded salt in the United States (particularly in Kansas) that is of satisfactory quality and in suitable geological environments that can be used for the burial of specified radioactive wastes produced by the nuclear plants that are anticipated in the United States over the next two to three decades.

8. The burial of the radioactive wastes under consideration in deep-bedded salt greatly reduces chances for release by accidental or malicious acts in both the near and distant future.

In addition, factors particularly applicable to the Lyons site are the following:

1. Salt formations suitable for radioactive waste burial can be found in areas with a low probability for earthquakes. The central Kansas area studied is so located.

2. The upward extrusion of bedded salt to form diapirs (dome formations) does not appear to be a reasonable possibility for the salt beds at the most favorable area under consideration by the AEC. The differential loading upon the salt beds is minimal. The relatively simple geological structure of the shallow beds, the low relief of central Kansas, and the tectonic stability are distinct advantages and militate against the development of salt flow. The increased temperature due to the planned thermal release of the radioactive waste and the pressure of the overburden, coupled with those items earlier discussed,

is inadequate to increase the plasticity of the salt to a level where extrusion by diapir formation is possible.

3. The westward retreat of the eastern edge of the salt front at the Lyons site has been estimated to be no greater than 12 miles in the last 5 million years. At this rate the geological disinterment of the Kansas salt beds in the vicinity of Lyons, because of the solution retreat of the salt, would not occur in less than 15 million years.

4. The salt beds in question are of Permian age (about 250 million years old). The fact that the salt has remained in place over this length of time is excellent testimony to the dryness of the geological environment of these beds and the prospects for safe interment for a significant geological time.

General Recommendations

1. The Committee judges that a sound case has been made for burial of highly radioactive solidified wastes in bedded salt. Sites correctly chosen with respect to design criteria and various factors identified below offer a satisfactory method for waste disposal in terms of present technology. Inasmuch as the AEC has announced the selection of a site near Lyons, Kansas, for the demonstration of long-term storage of solid high-level and of long-lived, low-level radioactive wastes, the Committee addresses its recommendations to the specific conditions of the Lyons site. However, many of the recommendations are applicable to other sites that might be as suitable as the Lyons site.

2. The Committe favors the development of the proposed method of burying low-temperature, low-level alpha-particle-emitting wastes in a salt mine at Lyons, Kansas, provided that appropriate limits are set on the integrity and combustibility of the materials to be buried. This type of waste must be buried in mined rooms separate from those in which the high-level wastes are buried.

3. Presently accomplished research, development, and design from the ONRL and other sources for the AEC are at such a state that the Committee can see no objection to proceeding with the plans for a demonstration facility for both types of wastes. The Lyons, Kansas, site offers a reasonable choice for such an initial demonstration project. Other sites such as those on the Gulf Coast, in Michigan, and in western New York should be considered for future use.

4. The Committee recommends that additional studies and investigations, described below, be undertaken concurrently with planning and site acquisition. If these studies and investigations reveal problems or conditions that would jeopardize the safety and integrity of the storage site, the project should be reconsidered. However, based on research and development performed to date the Committee does not anticipate any insurmountable problem.

Special Manageable Problems

Special problems that are judged to be manageable by technological controls and engineering methods:

1. The bedded salt deposits of Kansas contain minute quantities of included water that is gradually released at temperatures of 250 °C and above. Proper design of the spacing of the waste containers will reduce this problem to an acceptable level.

2. Radiolysis of salt is probably of little or no consequence. No free chlorine could be found in tests in the mine during Project Salt Vault. It is possible that a very small quantity of organic peroxides was produced. Ventilation methods that are already required for salt mining will further reduce the possible but extremely small hazard to the mine workers from any gases from this or any other source should they escape the salt bed containment.

3. If the salt temperature at the surface of the containers is held at 350 °C or lower, the temperature increases in a hypothetical overlying noncirculating potable water aquifer,* based on theoretical calculations, would not exceed 8 °C after about 800-1,000 years (the maximum increase in soil temperature at the surface will be less than 1 °C and would occur in about 800-1,000 years). The induced or natural movement of water through these aquifers will continuously effect a reduction of their temperature and even further diminish the significance of this potential problem (i.e., temperature increase) or will further reduce this potential temperature increase to a much lower figure.

*100 ft below the surface and 800 ft above the buried waste

4. The disposal of excess salt from the mining operation will require further engineering study. Several possible methods of handling this problem have been suggested. These include the sale of the salt for commercial use; solution in potable water and disposal in the Arbuckle Formation (the loss of potable water is undesirable); and solution in Arbuckle low-salt content water and return to the Arbuckle. It is also possible that an arrangement with a nearby mine could be made to return the excess salt to already excavated rooms. Other special mining techniques have been considered but not studied in detail. Another suggestion that has been considered is the disposal at sea in the Gulf of Mexico. The cost of this method including transport by rail and barge is high but need not be a reason for excluding it. The problem of the excess salt is a vexing one that has to be resolved. Since there are a number of potential solutions available, it is reasonable to expect that an acceptable solution can be developed, and therefore this problem is not sufficient reason to stop the program.

STUDIES TO BE COMPLETED BEFORE OPERATIONS BEGIN

Several site problems should be resolved before radioactive materials are committed to the salt beds. These problems are both geological and physical in nature. Four require investigations at the site, and one requires laboratory study.

1. In order to plan the location of the shafts and the distribution of the rooms in which disposal will be made, it is essential that the uniformity in quality and thickness of the salt beds be known. In order to obtain this information, some subsurface exploration is necessary.

Recommendation: Four cored and logged drill holes through the salt should be sunk at the corners of the approximately 1,100-acre proposed disposal site.

2. Location of previous oil and gas wells and inspection of records, where available, should determine if these former wells have been adequately plugged to avoid an entrance of water to the salt.

Recommendation: A survey should be made of neighboring wells in order to avoid threats to the integrity of the proposed bedded salt disposal site.

3. Subsidence in the distant future may result from void spaces after the rooms are backfilled with crushed salt.

Recommendation: An answer to this problem is required in order to determine the best mode of mining and backfilling. Model studies are suggested, e.g., block mining and block backfilling.

4. The possibility of a metamict (Wigner) effect due to high gamma radiation and the uncertainty about the accompanying marked temperature rise is a matter of moderate concern.

Recommendation: Experimental determination of the metamict effect in salt should be made using gamma-ray dosages equivalent to that expected under storage conditions.

5. A surrounding peripheral zone of approximately 1,000-1,500 feet in width must be protected from accidental drilling that might adversely affect the integrity of the demonstration site.

Recommendation: Control of this peripheral zone by purchase, lease, or other legal agreement is recommended.

CONTINUING DEVELOPMENT PROGRAMS

There are a number of development programs that are either under way or that should be initiated that, while not critical to the beginning of realistic planning and construction of a demonstration salt bed waste disposal project, may unexpectedly be the cause for a later decision not to continue. These programs will also be useful to the further development and evaluation of waste disposal in salt mines either at or near the Lyons site or, in some cases, for later projects elsewhere.

These programs fall into three categories: (1) exploration for the location of aquifers in the neighborhood of the salt beds; this includes determining the movement of the contained water and its proximity to the salt beds; (2) the development of further information on the thermal and mechanical properties of the salt beds and other key stratigraphic units; and (3) the investigation of methods of disposing of the large quantities of salt removed in the mining operation.

While the details of each program should be developed by the AEC and its consultants and will necessarily evolve as additional information is developed, the following items are suggested in connection with the three general areas identified above:

1. Movement of water in the neighborhood of the salt beds

The geology of the area should be examined to determine in greater detail the structural and stratigraphic characteristics. Particular attention should be paid to any indication of faults, sink holes, or other evidence related to structural erosional stability that might jeopardize the integrity of the salt bed.

Sufficient borings should be carried out to determine the geology of the area and the quantity and quality of the aquifers in the neighborhood of the salt beds. Additional tests may be desirable to determine the flow of the water in the aquifer if there is a possibility that this will affect the integrity of the salt beds.

Theoretical and experimental work should be carried out using cored material from the bedded salt area selected to determine the possible establishment of thermally initiated flow patterns that may dissolve and transfer material from the salt beds.

2. Thermal and mechanical properties of key geologic structures

The basic properties of the mixed salt bed materials (as found in situ) as well as other key materials should continue to be investigated to obtain additional information on thermal conductivity, thermal diffusion, thermal expansion, and phase changes (with volume and thermal effects), to the extent that these and other physical properties are needed for continuing evaluation of long-term disposal.

The determination of the properties of rock salt, such as viscosity, rates of plastic deformation, and solution rates, etc., should continue as a function of temperature, pressure, and time within the limits of conditions anticipated during long-term disposal of radioactive wastes.

3. While the disposal of the mined salt is to a considerable extent an operating and economic problem, some of the possible solutions require additional geologic and hydrologic investigation. The solutions for Lyons, Kansas, for example, include, as previously mentioned, the sale of salt, transport to the Gulf of Mexico, or disposal in mined-out areas in other nearby salt mines. Also the possible injection into the Arbuckle Formation of artifically concentrated brine requires additional studies of the hydrodynamic characteristics of the Arbuckle Formation and of possible chemical changes in the Arbuckle water.

LONG-TERM RESEARCH AND DEVELOPMENT

Some long-term considerationshave a relatively low order of priority since they have only a small probability of influencing the selection or operation of a burial site. These include

1. Waste retrieval plan
2. Postoperational monitoring (preceded by a determination of background data)
3. Estimate of subsurface leaching
4. Estimate of future rate of surface erosion

Investigation of most of these items is well under way and should be reviewed as completed. Conceptual information presented by the AEC to date has not included a waste retrieval or postoperational monitoring plan.

1. Problem: Contingency planning for retrieval of the radioactive waste from the salt has not been developed. A "worst possible case" hazards analysis is a matter of importance in the event that the integrity of the site is destroyed for any reason or if the operation does not perform according to design criteria.

Recommendation: For the preparation of such a contingency plan, consideration of systems for retrieving the waste, should it ever be necessary, must be developed.

2. Problem: A monitoring system is needed for postoperational surveillance of water quality and temperature, soil temperature, radiation levels, seismic activity, surface subsidence, plugged wells, and changes in the surface biota of both the contiguous land and waters after sealing the mine.

Recommendation: Adequate plans for such surveillance must be developed.

3. Problem: The eastern edge of the Wellington Formation outcrops at the surface, and there is evidence of a westward migration of this dissolving salt front, a condition that could destroy the integrity of the disposal site at a distant future time.

Recommendation: Data and interpretations should be formally prepared on the solutional history and regime of the eastern edge of the Hutchinson salt member of the Wellington Formation. The report should define the hydrologic conditions under which salt solution has occurred and evaluate the history and rate of solutional activity in order to determine whether the western migration of the dissolving salt front poses a threat to the future integrity of the disposal facility.

4. Problem: The extent of erosion that may take place in central Kansas during the next 500,000 to 1,000,000 years conceivably may affect the integrity of the repository. The near-surface rocks and regional geomorphic and hydrologic aspects of any storage site, including the Lyons site, represent a response to geological processes operative during Pleistocene time. Many geologists agree (and this Committee accepts the

idea for the purposes of this report) that the present is part of the continuum of the Pleistocene and that similar processes may be operative during the next 500,000 to 1,000,000 years, the span of time for maintenance of the integrity of the waste disposal site. During the past million years, for example, the effects of glaciation have produced marked changes in groundwater systems, drainage systems, and surface erosional rates. The long-term possibility that the bedded salt may be subjected to solutional activity, erosion, or other stresses cannot be ignored.

Recommendation: The extent of future erosion may be projected by statistical treatment and extrapolation of recent rates of erosion in several climatic zones that would be representative of the kinds of climate that may have existed in the midcontinent during the last million years. These conditions conceivably could be expected to prevail or recur during the next million years. Studies should be initiated of the effects of changes in the Arkansas River systems, changes in groundwater circulation, long-term changes in land form, and evaluation of the long-term possibility that the salt may be subjected to erosional or solutional activity. The Committee believes that this recommendation should be given a low priority since ample time exists for decisions regarding it at a much later date.

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APPENDIX: BASIC CHARACTERISTICS OF THE WASTES AND CONSIDERATIONS FOR THEIR BURIAL

The two categories of wastes for which the salt repository is being designed are (1) solidified high-level radioactive wastes generated by the reprocessing of irradiated nuclear power reactor fuels, and (2) solid waste contaminated with low-levels of radioactivity, principally the transuranium elements such as plutonium. To ensure maximum safety, the AEC intends to specify and rigidly control the nature of the wastes that will be accepted for burial.

HIGH-LEVEL WASTES

The two significant considerations in the development of specifications for the solidified high-level wastes and the design criteria of the repository are (1) heat generation, and (2) internal pressure within the containers.

Heat Generation

Because the solidified wastes will generally be stored at temperatures hundreds of degrees lower than the temperatures experienced during solidification, the thermal effects on the wastes during storage should be negligible. The thermal energy released from the stored waste is only of significance in relation to its effect on the structural properties of the surrounding salt.

In Project Salt Vault, an experiment performed in the Carey Salt Company's mine at Lyons, Kansas, it was determined from measurements made of the plastic characteristics of salt at elevated temperatures that the integrity of the active mine workings could be maintained provided the temperature of the salt did not exceed 200° C at the midpoint between adjacent containers. This temperature limitation can be maintained by limiting the total power in any single 10-ft long container to 7,500 W (25,000 Btu/hr) and by spacing the containers so that the centerline temperature of a container does not exceed 900° C and the temperature of the salt at a distance of 8 in from the container does not exceed 250° C. The actual thermal output of the containers will be verified both by records supplied by the reprocessor and by calorimetric measurements made at the repository prior to burial.

The thermal power of a typical can of high-level solidified waste (6 in. in diameter by 10 ft long) is 530 W at 10 years, 55 W at 100 years, and 1 W at 1,000 years.

The containers will be fabricated from either carbon steel or stainless steel, and may vary from 6 to 24 in. in diameter, from 2 to 10 ft in length, and, when filled with waste, may weigh up to 6,000 lbs. each.

The question has been raised regarding the migration of "hot" waste containers through or out of the salt. Simplified analyses have been performed using conservative assumptions that indicate that the migration of waste containers in 250°C salt would be in the order of 10-10 in/yr. If it is postulated that the waste could migrate from the disposal plane, it would travel into salt of lower temperature, and this would gradually cool the waste and terminate its movement. Additionally, the shale partings present in bedded salt deposits would act as a physical barrier to limit the movement of the waste. It is reasonable to conclude that the containers will not migrate to any significant extent.

A further question has been raised as to the possible effects of energy storage within the waste and the salt as a result of irradiation (metamictization). The storage and sudden release of energy from containers buried in the repository appears unlikely because the mine temperatures are in the range of annealing temperatures, and the waste temperatures are above them. Even if energy storage and sudden release did occur, the effect on mine temperature would be insignificant. Storage of amounts of energy above about 500 cal/g has not been observed in silicates similar in composition to some types of wastes, and the sudden release of this quantity of energy would raise the temperature of the salt 5 ft from the container by only about 2°C. Storage of energy in salt should not exceed 20 cal/g, and its release would not have seriously deleterious effects.

Internal Pressure

The internal pressure of the waste containers after burial is expected to be of little consequence because the waste will be solidified at temperatures in excess of those expected during transport and storage. Several of these containers are presently being stored with molten cores (> 1,100 °C), a condition which would not be expected under storage in the mine. To date, no pressure buildup has been noted in any of the containers. This would suggest the absence of any significant decomposition of the solidified products because of heat or radiation.

The pressure-related requirements that will be imposed are (1) that the solidified product be thermally and radiolytically stable and (2) that the equilbrium pressure within a waste container be less than the design pressure rating of the container. (The latter is actually redundant because of requirements imposed via the regulatory process in the safety analysis of the interim waste storage and transportation systems.)

LOW-LEVEL WASTES (TRANSURANIUM NUCLIDE CONTAMINATED WASTE)

These wastes are solid materials that either contain or have surface contamination of plutonium or other transuranium nuclides. Any waste material containing or contaminated by detectable quantities of plutonium is classified as this type

of waste. (The present detectable limit for plutonium waste is 500 mg/ft^3 for a 5 ft^3 package.) Such wastes include failed or obsolete equipment, contaminated tools, paper, clothing, construction rubble, nonreclaimable fabrication scrap, solidified liquid waste, etc.

The bulk of the wastes are packaged in metal drums (55-gal barrels). Larger pieces are boxed in varying sized containers. The container shields out essentially all radiation and presents minimum handling problems from that standpoint. However, the contaminant, usually plutonium, is very long-lived and very hazardous if inhaled or ingested. The major health hazard is usually associated with resuspended airborne particulates; therefore, the containers must maintain their integrity and must themselves be externally free from the contained contaminants.

The initial heat generation rate of these wastes will be limited to about 0.1 watt/ft^3, and the thermal power will not exceed 0.01 watt/ft^3 at any time greater than 1,000 years after their receipt at the repository. Criticality safety will be ensured by limiting the average fissile concentration to 5 g/ft.^{3} Combustible wastes will not be accepted for storage in the repository until it is established that storage of such wastes presents no fire hazard.

The estimated average annual off-site concentrations of airborne radioactive particles from the repository will be no greater than 0.1 percent of the permissible concentrations for exposure of a suitable sample of a population group.

GEOLOGY AND HYDROLOGY OF THE SALT BEDS

The Hutchinson member of the Wellington Formation is approximately 300 ft thick at the Lyons site and lies between 780 ft and 1,080 ft below the surface. The Hutchinson is composed of about 60 percent halite (NaCl) that is interbedded with shale and anhydrite ($NaSO_4$).

There are three freshwater-bearing zones above the salt. The deepest of these lies from 275 to 290 ft below the surface and will yield water at a rate of 1 to 3 gal/min. Sandy members of the Kiowa shale formation that occur at depths of 50 to 175 ft will yield water at a rate of from 1 to 20 gal/min. The unconsolidated blanket of sediments that extend to a maximum depth of 70 ft will yield 1 to 5 gal/min. No freshwater aquifers are found below the salt; however, beginning several hundred feet below it, some porous and permeable zones are encountered that contain salt water. In all cases, the water-bearing zones are separated by thick sequences of essentially impermeable shales.

MINE SPECIFICATIONS

It is planned that all new shafts into the working area will be round, drilled from the surface, lined with heavy-wall metal casing and fully cemented. These holes will also contain an outer surface casing to a depth of 300 ft, which will isolate the casing and its cement from all known aquifers. For the

existing shaft, or any new shafts conventionally sunk rather than drilled, the aquifers will be pressure sealed and/or lined with concrete, poured in place. These precautions will effectively prevent water from entering the mine through a shaft.

In the present concept, the specifications for the new shafts are as follows: (1) high-level waste shaft, 33 in. inside diameter; (2) downcast ventilation, service and salt hoisting shaft, 14 ft diameter; (3) upcast ventilation shafts, 6 ft diameter. The shaft sizes are strongly dependent on the details of underground operations, which are currently undergoing extensive investigation by Kaiser Engineers. Therefore, these sizes may change drastically in the final concept.

All shafts will be eventually backfilled as part of the decommissioning of the repository. Present plans call for filling them with successive layers of crushed salt, shale, gravel, and sand. Impervious seals at critical elevations would be provided by layers of a bentonitic clay.

In the present concept, all newly mined openings in the high-level waste disposal area (main entries, corridors, and rooms) are 30 ft wide and the rooms are separated by 30-ft-wide rib pillars, while 50-ft-wide pillars are left between all dual corridors and entries. Based on preliminary analysis of Project Salt Vault data, these dimensions should be close to the optimum, but they will be refined by further analysis before the excavation starts. The final design will

then be verified and refined further, based on instrumentation that will be placed in the first few rooms of the actual facility. "Optimum," in this case, means those dimensions that will provide (a) the maximum amount of usable space per unit of gross area, consistent with (b) safe and trouble-free operation of the mine during excavation, waste disposal and backfilling, while allowing (c) the earliest practical complete closure of the mine and recrystallization of the backfill salt (currently estimated to occur within 65 to 100 years after filling).

TRANSPORTATION OF WASTES AT THE MINE

Waste cans will be unloaded remotely from their shipping cask in a shielded hot-cell at the surface and lowered in a cage through the waste transfer shaft to the mine level. Both this shaft and hoist will meet the requirements of 30CFR57 for a man-riding hoist. The salt mine will be developed over the life of the repository and will provide space for storage of high-level waste cans. Various methods for handling the cans in the mine are currently under study. In the case of one concept that has been given consideration, the cans will be received at a mine-level receiving station and loaded directly into shielded casks carried by motorized transporters. They are then carried by the transporters to rooms mined in the salt formation and buried in vertical holes in the floor. After the floor area of a room has been utilized, the room will be backfilled with crushed salt and sealed from the remainder of the mine.

POPULATION DENSITY OF THE LYONS, KANSAS, AREA

The following figures, based on the 1970 census, provide an indication of the population density in the general area:

City of Lyons:	4,306 (area, approximately 1.5 sq mi) 2,876/sq mi
Rice County:	12,129 (area, approximately 800 sq mi) 15/sq mi
Sampling of 12 rural townships:	maximum population density 72/sq mi; average, 3.9/sq mi; minimum, 0.9 sq mi.

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FERRUCCIO GERA *Federal Repository Project, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830*

Review of Salt Tectonics in Relation to the Disposal of Radioactive Wastes in Salt Formations

ABSTRACT

The plastic deformation of salt formations is reviewed to evaluate the possibility of diapiric processes affecting salt beds used for radioactive waste disposal. In a geological sense, rock salt is characterized by a marked mobility as a result of its ability to deform under relatively low stresses. Examples are known of salt formations deformed by tectonic forces, but the typical diapiric processes are essentially due to gravitational forces. In the initial phase, salt deformation is caused by differential loading of the salt bed: only after salt flowage has resulted in thickening of the low pressure zones of the salt bed does the density difference between salt and sediment contribute to the deforming stress. Salt diapirs are usually large structures, and to furnish the necessary large volume of salt, a mother bed of great initial thickness must be presumed. No minimum depth seems to exist for the plastic deformation of salt; however, the plasticity of salt increases with depth as a result of the increasing temperature.

The rate of salt deformation is critical in relation to the required containment time for plutonium-contaminated waste. A few authors maintain that diapiric processes proceed at a catastrophic rate, but the geologic literature indicates that most geologists believe salt diapirism to be a relatively slow process and geologic evidence seems to support strongly the majority view. It can be concluded that, in the final stage of salt intrusion, rates of diapir growth as high as a few millimeters per year are possible, and in the initial phase of plastic deformation of the salt bed, flow rates should be markedly lower.

In relation to the safety of radioactive waste containment, the risk of excessive deformation can be kept acceptably low if the disposal formation meets the following requirements: (1) bedded salt located in a geologically stable area; (2) subhorizontal salt beds exposed to very limited differential loading; (3) thickness of the salt beds of the order of 100 to 300 m; and (4) depth of the salt beds between 300 and 700 m.

INTRODUCTION

Salt formations have been proposed as the safest location for the disposal of radioactive wastes requiring long-term containment. To evaluate the possibility of diapiric processes affecting the long-term stability of the waste repository, a thorough understanding of all aspects of salt diapirism is necessary. Diapirism is a process by which earth materials from deeper levels deform and pierce overlying materials. The actual piercement of the overburden is usually the final stage of a complex history of "plastic" deformation. (In the geological literature, the term "plastic" is applied to the continuous deformation of complex solid bodies, such as rocks, in contrast to the viscous flow of fluids. It is used without any implication about the mechanisms responsible for the deformation.)

Evaporites are not the only geologic materials capable of forming diapiric structures. Argillaceous sediments before induration show a marked ability to flow. In addition, serpentine and occasionally limestone, coal, and peat are found as diapiric materials (O'Brien, 1968).

This discussion is limited to the deformation of rock salt, but the basic principles are applicable to other geologic materials. All rocks, given sufficient stresses acting for geologic periods of time, undergo some creep or plastic deformation. In competent rocks, however, the rate of deformation is too low to cause evident flowage. Salt owes its geologic mobility to its ability to deform readily under relatively low stresses.

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PHYSICAL PROPERTIES OF SALT

Rock salt is an aggregate of halite crystals. The individual halite grains usually have dimensions of a few millimeters, although crystals as large as several centimeters are found. Halite crystallizes in the cubic system; its hardness is 2.5 and density is 2.165 g/cm³.

Rock salt always contains some impurities, and the amounts can vary between wide limits. Although impurities in bedded salt are essentially primary or a result of contemporaneous sedimentation, diapiric salt can contain exotic blocks torn from the intruded formations. Among the primary impurities, anhydrite and clay minerals are by far the most abundant.

Some of the parameters affecting the physical behavior of salt can be evaluated from the deformation of salt specimens in laboratory tests (Handin and Hager, 1957, 1958; Handin and others, 1963; Robertson, 1963; LeComte, 1965; Handin, 1966; Odé, 1968). In a general way, when a gradually increasing stress is applied, the specimen first deforms elastically, regaining its original dimensions if the stress is removed. The stress at which an appreciable permanent deformation is first observed is known as the yield stress. For specimens of halite in its original depositional form, the stress-strain curve is of the type of the solid line A-D in Figure 1. No distinct yield point is evident, but the deformation is almost completely elastic only up to about 10 kg/cm². If the stress is raised to 100 kg/cm² and released, as in B, about 0.4 percent of permanent deformation remains (Borchert and Muir, 1964). When stress is applied again, the deformation curve is CBD; the curve now has a straight segment CB, where deformation is essentially elastic, and shows a distinct yield point at B. The strengthening of the mineral with increasing deformation is called "strain hardening" or "work hardening." Salt with a geologic history of deformation or of burial only is always in a somewhat strengthened state. Relaxation and recrystallization may cause salt to return to the initial unstrengthened state. Figure 2 shows the effect of annealing a sample of Lower Halite at 600° C. The sample under consideration was taken from a mine, and how much of the strengthening is a result of the mining operations is not known (Borchert and Muir, 1964).

The physical behavior of salt is drastically affected by temperature. Not only does the rate of deformation increase with the temperature, but the strain-hardening effect is progressively reduced; at 300° C it disappears completely, and salt deforms at a constant rate if constant stress is maintained. At constant temperature the rate of deformation of salt crystals is inversely proportional to the confining pressure. The effect of confining pressure is, however, very limited. Figure 3 shows the effect of temperature and confining pressure

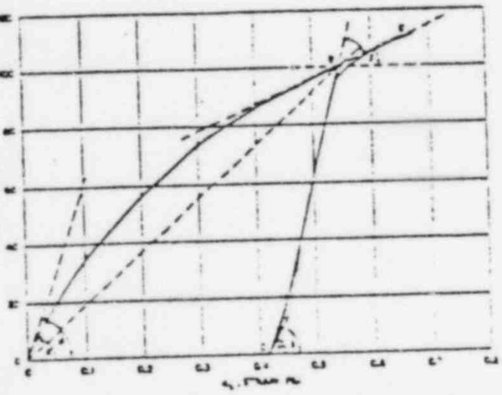

Figure 1. Quasistatic deformation of a sample of the Stassfurt Halite showing the effect of temporary release of stress, the amount of permanent deformation produced, and the distinct yield point produced when the sample was stressed once more (*from* Dreyer, 1955).

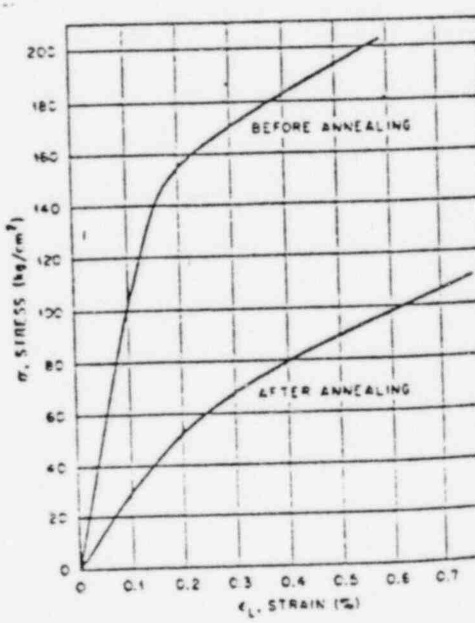

Figure 2. Effect of annealing at 600° C on stress-strain curves of samples of the Stassfurt Halite. (Modified *from* Dreyer and Borchert, 1955.)

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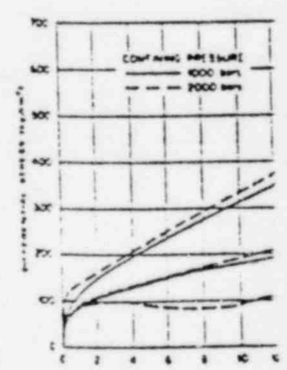

Figure 3. Stress-strain
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on the deformation of halite crystals. It is evident that the effect of confining pressure is secondary. In nature, the ease of deformation of salt increases with depth, because the increase of temperature with depth overrides the effect of the increasing confining pressure. At a depth of 9,000 to 10,000 m, assuming a geothermal gradient of about 30° C per km, the temperature would be about 300° C and the deformation would occur without any strain hardening. Other parameters are known to influence the creep of rock salt. LeComte (1965) has found that the creep rate is proportional to the stress difference and that an increase in grain size reduces the creep rate. In addition, the deformation of salt is influenced by the rate of change of stress. In nature the buildup of stress difference on a salt formation is a very slow process. Additional parameters affecting the large-scale deformation of salt formations are the thickness of the salt beds, the amount and nature of the impurities contained in the salt, and the presence of fluids. In the individual halite crystals, the principal mechanism of deformation is by translation gliding on the dodecahedral crystallographic planes, although some translation gliding may also occur on the cubic planes (Clabaugh, 1962).

Where salt has undergone extensive deformation, a certain preferential orientation of the salt grains should be evident. However, the few petrofabric studies on salt specimens from the Gulf Coast area are not conclusive (Clabaugh, 1962; Muehlberger and Clabaugh, 1968; Carter and Heard, 1970), but where anhydrite is abundant, the orientation of the

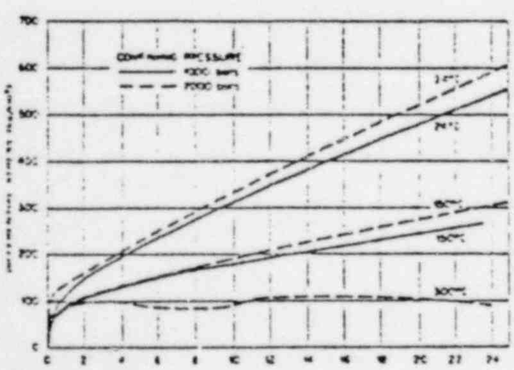

Figure 3. Stress-strain curves for halite single crystals deformed dry in compression at 1,000 and 2,000 bars confining pressure and at different temperatures (from Handin and Hager, 1958).

anhydrite crystals in the direction of movement is evident (Balk, 1949).

In conclusion, the physical properties of halite in the laboratory are fairly well known, but the deformation of salt formations in nature is poorly understood. The best way to learn about the physical behavior of salt in nature is not by the extrapolation of laboratory experiments, but by the study of geologic structures caused by the deformation and flowage of salt.

SALT DEFORMATION

Evaporites are very common sediments and, with the exception of shield areas, they are found in all parts of the world; in age they range from Precambrian to Holocene. Because of their high mobility, at least in a geologic sense, evaporites that are or have been buried to a certain depth usually show some deformation. When a postdepositional movement of the salt relative to overlying and underlying strata has occurred, salt structures have been formed. Salt structures vary from salt bed thickening caused by moderate flowage of salt to very large diapirs, where tens or even hundreds of cubic kilometers of salt have been intruded through the overburden. Examples of all possible intermediate structures are known, and a complex terminology has resulted from the descriptions of these situations.

Salt anticlines are linear structures in which salt has accumulated and arched the overlying strata, but no piercement has occurred. Salt pillows and salt ridges are similar to salt anticlines, usually with a more advanced accumulation, but still no piercement. Salt walls are linear structures with very steep or subvertical flanks. From the linear structures, the localized accumulation of salt in areas of minimum overburden pressure can result in the formation of structures with subcircular and circular horizontal section. A subcircular accumulation of salt that lifts the overburden without piercing it is called a salt uplift.

When salt has broken through and penetrated any of the overlying beds, the structures have been designated as salt diapirs, salt domes, salt chimneys, salt plugs, salt stocks, and salt eczemas. The term salt dome seems to describe a salt uplift satisfactorily, but unfortunately is generally used in relation to piercement structures. Where several diapirs merge at depth into a salt ridge, the whole complex is called salt massif.

Driving Forces of Salt Deformation

Forces resulting from the weight of the overburden are always acting on every salt bed or salt structure. In addition, horizontal compression due to tectonic movements may also be present. In some areas (for example, in Romania), tectonic forces have obviously been important in the deformation of salt, but in other areas the forces responsible for salt deformation must have been exclusively gravitational.

When a salt bed is exposed to different pressures at different points, for any reason, a pressure gradient in the salt will result. If this pressure difference is sufficient to deform the salt, plastic flowage will occur. When salt is driven along the mother bed from high-pressure to low-pressure areas, a geometrical change occurs that necessarily influences the surrounding strata. The overburden must be uplifted over the zones of salt accumulation, and it must be downwarped, or grabens must be formed, over the areas from which salt is squeezed out. The mode by which the overburden adjusts to the deformation of the salt bed is controlled by its physical properties. While incompetent materials follow the salt mainly by stretching and folding, competent strata may undergo extensive faulting. A very strong and rigid overburden could even prevent salt deformation altogether. Once the variations in thickness of the salt bed, because of salt flowage, are established, the difference in density between salt and overlying sediments begins to play a part that gains importance with the progress of salt accumulation. While the density of salt is fairly constant at 2.2 g/cm^3, the bulk density of terrigenous sediments is a function of the compaction that they have undergone.

The density difference between salt and sediments influences the deformation process, because it affects the pressure applied to a horizontal reference plane located in the salt body. Figure 4 shows diagrammatically the development of a salt diapir. Let us consider an imaginary horizontal plane on which are located the points a and b; the vertical lines going through a and b intersect the boundary between salt and overburden at a'' and b'' and intersect the surface at a' and b'. In stage 1 all beds are horizontal and no differential loading should exist, unless the density of the overburden is not uniform.

In stage 2 a pressure difference has developed because of the difference in density between salt and sediments. The load at b is equal to the weight of a salt column with height bb'' plus a sediment column with height $b''b'$. At a the load is $aa'' + a''a'$. It is clear that the higher the salt structure becomes the greater the pressure difference between a and b as a result of the density difference between salt and sediments. In stage 6 the pressure difference is at a maximum but no salt is left at b; therefore, no further deformation is possible. A very important point is that prior to any deformation the difference in density between salt and sediment has no effect whatever.

Gussow (1968) has calculated that at the base of a diapir 8,500 m high located in the Gulf Coast area, the differential pressure due to the salt-sediment density contrast would be about 160 to 170 kg/cm^2. The above considerations are valid only as long as differential sedimentation between rising and subsiding areas or erosion of the uplift, or both, keep the surface horizontal. If the rising salt compacts the overburden, thus increasing its density, or if no differential sedimentation and erosion take place, the pressure at a would increase progressively, and eventually the pressure difference driving salt from b to a would become insufficient to maintain the flowage.

Piercement of the overburden and intrusion of the salt can only occur when the stress exerted by the rising salt exceeds the shear strength of the cover. Logically, salt deformation should be influenced in a very significant way by the physical properties of the surrounding rocks. In many instances the overburden has behaved as an incompetent complex following the deformation of the salt bed. However, at the time of the diapiric intrusion, extensive faulting of the overburden occurs, and the distrubance of the intruded strata can be very marked.

The faulting associated with the intrusion of salt diapirs proves that the overburden behaves as a solid that has been exposed to stresses in excess of its shear strength. The diapiric salt rises as a plug pushed from underneath. Because of the plasticity of the salt, the shape of the plug will adjust to the distribution of pressures surrounding the salt. For example, when salt approaches the surface and rises through unconsolidated sediments with density lower than 2.2, some lateral spreading of the

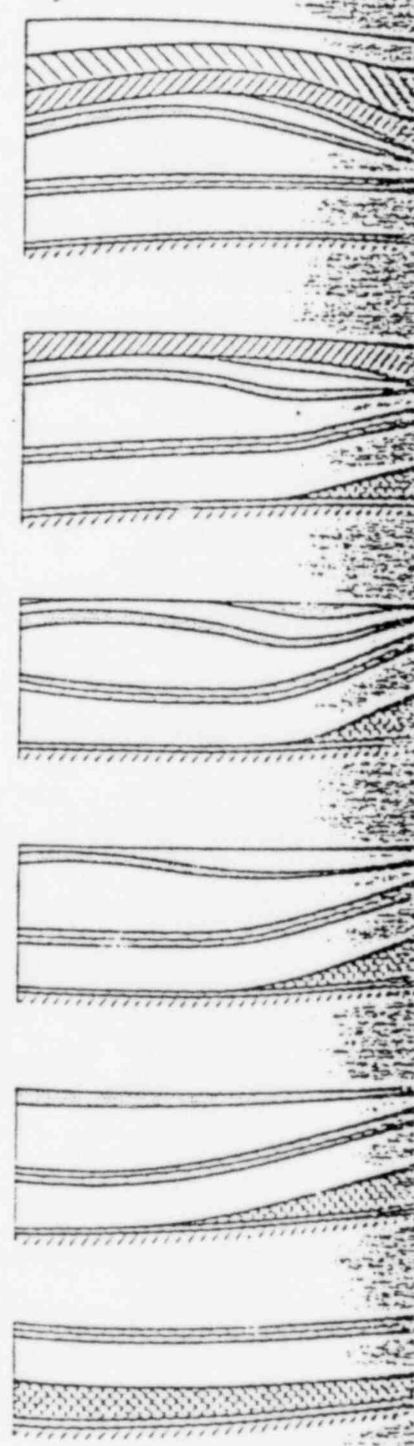

Figure 4. Diagrammatic development

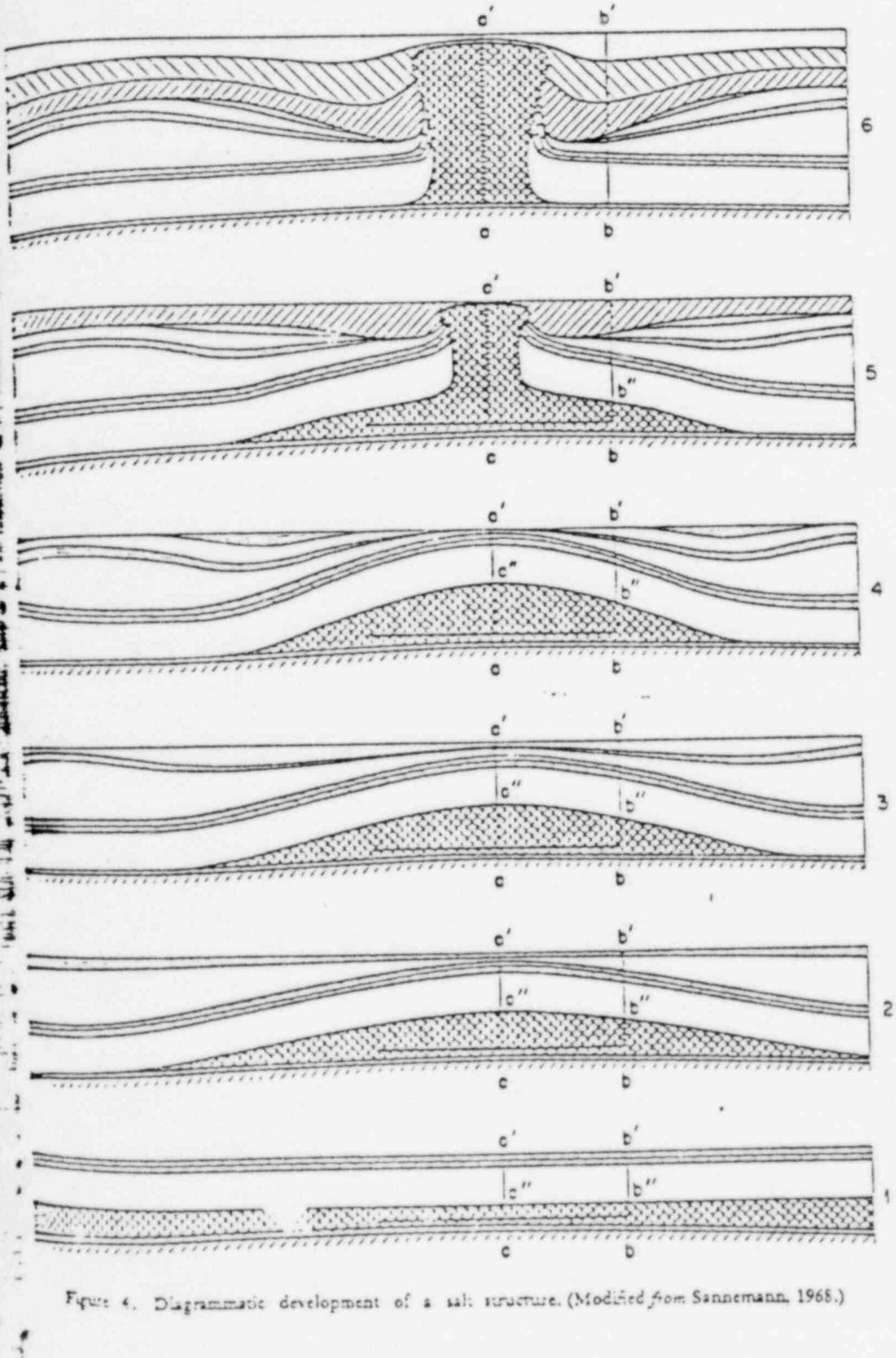

Figure 4. Diagrammatic development of a salt structure. (Modified *from* Sannemann, 1968.)

salt plug can occur because of the weak confinement that the sediments afford. The study of the internal structures of several salt domes of the Gulf Coast area suggests that the salt plug advances in spines and lobes separated by shearing planes. The movement of the salt is probably jerky and discontinuous, being controlled by the interplay of several factors, mainly work hardening of the salt, relaxation and recrystallization, and resistance of the overburden (Balk, 1949; Muehlberger, 1959; Kupfer, 1968).

Necessary Thickness of Mother Bed

Geological data indicate that a minimum thickness of the salt mother bed of the order of 300 to 400 m is required for the development of diapirs. To prove that a minimum thickness of the mother bed must be necessary, it is sufficient to analyze the known facts about salt diapir dimensions. A typical salt diapir is circular to oval in section, with a diameter of 2 to 15 km, and the height, although frequently unknown, is at least several thousand meters. In the Gulf Coast area, the depth of the mother bed is a minimum of 8,000 to 9,000 m. In other areas the mother bed is much closer to the surface; in the east Texas and north Louisiana synclines, the depth to the Louann salt ranges from 3,000 to more than 4,500 m (Atwater, 1968). In the German salt basin the depth of the mother bed ranges between 3,000 and 5,000 m (Trusheim, 1960). In northern Algeria the total depth to the diapiric Triassic complex is on the order of 3,500 to 4,000 m (Bertraneu, 1957). In southern Iran the depth to the mother bed is usually 6,000 to 8,000 m (Harrison, 1930; Kent, 1958). Therefore, it is clear that the volume of salt involved in single diapirs is many cubic kilometers. In addition to the classical salt diapirs of cylindrical shape with nearly vertical flanks, many bell-shaped diapirs, resembling truncated cones, are known. The volume of salt contained in cone-shaped structures can be enormous. For example, the Lake Washington dome, Plaquemines Parish, Louisiana, contains 200 km^3 of salt down to a depth of about 5,000 m. The depth of the mother bed is unknown, but it is safe to state that the total volume of salt in this structure must be well in excess of 1,000 km^3 (Atwater and Forman, 1959). Even larger salt structures are known; for example, Atwater and Forman (1959) estimate that the salt massif formed by the merging at depth of the Bay Marchand, Timbalier Bay, and Caillou Island diapirs, in the Louisiana Gulf Coast, contains in excess of 5,500 km^3 of salt. The initial thickness of salt in the source area of the Marchand–Timbalier–Caillou Island salt massif has been calculated by the same authors. They state that the volume of salt now present in the massif, if distributed uniformly in the source area, would result in a salt bed with a thickness of the order of 4 to 5 km.

In many cases it is evident that the volume of salt in the salt structures is only part of the total salt present in the basin. When the source areas of different salt structures are well defined, it is possible to identify areas from which salt has not been drained. Even when the source areas are unknown, it seems likely that some salt is left in the mother bed, at least at a distance from the salt structures. In addition, large volumes of salt have been removed from many structures by dissolution or erosion, or both. When the volume of cap rock and the salt composition are known, it is possible to estimate the amount of salt that had to be dissolved for the accumulation of the caprock formation, but if salt was extruded at the surface, as in southern Iran, there is no way to calculate the volume of missing salt.

The extent of the source area can be estimated from the spacing between diapiric structures in a diapiric family and from the dimensions of well-developed peripheral sinks. The term peripheral sink was proposed by Nettleton (1934) to describe the depression in the salt bed, caused by the squeezing of the bed as salt moves into the area of salt accumulation. The downwarping of the overlying strata into the peripheral sink results in the feature called rim syncline. The rim synclines formed in the initial stage of salt deformation are called primary, distinct from the secondary rim synclines that are formed in the stage of diapiric intrusion.

If the primary rim syncline can be reconstructed, the amount of primary subsidence is an indication of a possible "minimum" original thickness of the mother bed. However, in many areas the primary sinks are too deep for observation, and the known rim synclines are only the relatively shallow expression of deformation occurring during the last stage of the evolution of the salt structures. Ritz (1936) has stated that the top of the McElroy (Jackson, Eocene) Formation is a good marker horizon in the northern part of the Gulf Coast area and that it can be used in mapping sub-

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surface structures; the horizon is deeper than normal adjacent to all salt diapirs. For example, on the east side of San Felipe dome, Waller County, Texas, the top of the McElroy is about 600 m below its normal depth in the area. Near Hockley dome, Harris County, Texas, the same marker horizon is approximately 450 m below normal (Parker and McDowell, 1955). This means that a minimum thickness of salt, 600 and 450 m, respectively, has been squeezed from underneath these peripheral sinks. However, the whole story of salt accumulation should be reconstructed if the original thickness of the mother bed is to be inferred from the evolution of the rim synclines.

It should also be considered that original variations in salt thickness along the mother bed can be caused by sedimentary processes that result in differential accumulation. Another process that might cause areas of exceptional salt thickness is the downslope sliding of sediments. Gravity sliding is known to play an important role in the evolution of sedimentary basins, and the process would be expected to be especially active in sequences of evaporites and fine sediments (Dott, 1963; Lehner, 1969; Amery, 1969).

The thickness of 4 to 5 km of salt calculated by Atwater and Forman for the source area of the Marchand–Timbalier–Caillou Island salt massif is probably a case of salt thickening by syndepositional or postdepositional mechanisms, since the concept of the accumulation of 4 to 5 km of salt in the entire Gulf Coast basin is clearly unacceptable (Atwater and Forman, 1959).

NECESSARY DEPTH OF BURIAL

The existence of a thick layer of salt, although necessary, is not a sufficient condition for the formation of salt diapirs. Sannemann (1968) mentions large areas in Germany where Zechstein salt, with a thickness of 1,000 m, shows little or no sign of deformation. For example, northwest of the salt-stock family north of Hamburg is a large area where Zechstein Salt about 1,000 m thick, covered by 3,000 to 4,000 m of sedimentary overburden, lies on a basement rising northward with a slope of 1° to 2°. Apparently, no salt deformation, even to the initial stage of salt pillows, has occurred; instead the salt has maintained its original uniform thickness (Sannemann, 1968). Therefore, burial under a sedimentary cover 3,000 to 4,000 m thick is not in itself a sufficient condition to initiate the flowage of salt. In other areas of Germany there is good geologic evidence that salt deformation started when salt was only 2,000 to 2,500 m deep (Roll, 1956). It is clear that there is no distinct minimum depth of burial separating deformable from competent salt beds. Although the ease of deformation of salt undoubtedly increases with depth because of the increase in temperature, the only critical factor in the deformation process is the pressure difference to which salt is exposed.

To reconstruct the initial phase of salt deformation, it is necessary to analyze the variation in thickness of the beds of various geologic ages, so that the development of the rim synclines can be determined. This can be done only if abundant data from boreholes and from seismic profiles are available. Sannemann (1968) reports the example of a salt-stock family, located west of Bremen, for which the ages of the rim synclines of the individual diapirs are known (see Fig. 5 for the spatial relations and ages). The Arngast diapir has a

Figure 5. Characteristic part of salt-stock family in northwestern Germany (*from* Sannemann, 1968).

rim syncline of Keuper age (Upper Triassic): the Etzel and Strackholt diapirs are Liassic (Lower Jurassic); the Jaderberg diapir developed in the Dogger (Middle Jurassic); and the Scharrel and the Zwischenahn structures have a rim syncline of Malm-Cretaceous age (Malm = Upper Jurassic). Even farther south, the Neuarenberg diapir has a Tertiary rim syncline. The deformation has moved as a wave from north to south in a time period of about 100 m.y. In Keuper time, when the rim syncline of the Arngast diapir was formed, the mother salt bed was buried at a depth of 2,000 to 2,500 m. Whether the stress gradient, necessary for salt flowage at such relatively shallow depth, was caused only by differential loading or by a combination of gravitational and tectonic forces is not clear. However, if tectonic movements occurred, as seems likely, they were limited to triggering the salt deformation through folding. Once folds were formed, differential accumulation between synclinal and anticlinal areas furnished the stress difference necessary for the flowage of salt.

Influence of Overburden

Piercement of the overburden and intrusion of the salt can only occur when the stress exerted by the rising salt exceeds the shear strength of the overburden. The physical properties of the overburden are therefore an important parameter in determining the development of the diapiric process. The resistance that the overburden offers to the salt intrusion is a function of the shear strength and thickness of the rocks. Salt diapirs are generally located in sedimentary basins characterized by extensive subsidence and accumulation of great thickness of sediments. In such sedimentary environments, terrigenous sediments prevail; these shale and sand layers are usually quite incompetent. However, cases are also known where the salt has pierced competent rocks. In the northeastern Texas and northern Louisiana areas, the Louann mother bed is overlain by Late Jurassic and Cretaceous strata in which calcareous facies are well represented. The thickness of strata in which limestone prevails is of the order of 2,000 m, but the rigidity of the overburden was insufficient to prevent the formation of well-developed rim synclines (Atwater, 1968).

However, an overburden of remarkable strength and rigidity can effectively limit the plastic deformation of the salt bed. If piercement should occur anyway, the formation of rim synclines might be impossible; instead, the overburden would adjust to the deforming salt bed by the movement of faulted blocks. An important consequence of the lack of a well-developed peripheral sink could be that no cutoff of the diapir from the source area would occur, and therefore salt intrusion would be arrested only by an insufficient pressure difference or by depletion of salt in the mother bed. South Iranian salt diapirs have a number of features that might be related to the unusual strength of the overburden.

Iranian Diapirs

In southern Iran the mother bed of the diapiric salt is located at unknown depth that could be even greater than the estimated 6,000 to 8,000 m. Strong, competent rocks are well represented in the thick overburden (Harrison, 1930; Kent, 1958). Whether the pressure differences caused by differential loading did actually fracture several thousand meters of strong, competent overburden is open to question. If the contribution of tectonic forces and the intrusion along prediapiric faults is proposed, a certain degree of alignment should be recognizable, but this does not seem to be the case. On the other hand, possible prediapiric tectonic alignments might be masked by the more recent geologic history, especially the Zagros orogeny of late Pliocene time. The most probable solution, therefore, is that the salt deformation and the rise of the salt diapirs lasted for a long part of the subsidence of the basin. In this case the salt plugs never had to break through the total thickness of overburden. Extensive faulting is evident, especially in the Tertiary limestones, that could be related to salt diapirism.

The intrusive salt, probably of Cambrian age, typically carries with it a disorderly assortment of sedimentary, igneous, and occasionally metamorphic rocks. None of these materials outcrops in the area nor do they have a counterpart in the normally exposed stratigraphic sequence. The complex of allochthonous materials is known as the "Hormuz Salt Formation" or "Hormuz Series."

The large amount of exotic material that the salt has torn from lower levels and transported to the surface might be a consequence of the rigidity of the encasing formations. The dimensions of most exotics are of the order of a

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few or several meters but a few are very large. Kent (1958) mentions cases of Paleozoic blocks 1,000 to 1,500 m across. The uniqueness of the allochthonous materials of the Hormuz Series occasionally provides geologic evidence of the time when individual salt diapirs reached the surface. If a conglomerate, close to a diapir, contains fragments of Hormuz rocks, and if the age of the conglomerate is known, it is conclusive evidence that during the accumulation of the conglomerate the diapir had already reached the surface and was undergoing erosion. For example, the Khormuj salt diapir gave rise to conglomeratic beds of Hormuz detritus interbedded in the lower Eocene; therefore, in this case, a very ancient extrusion is demonstrated. Many other diapirs reached the surface in Miocene time. The fact that many diapirs were already at the surface in the Miocene is very important, because the Mio-Pliocene complex exceeds 4,500 m in thickness and is in great part responsible for the strength and rigidity of the overburden. The Miocene is marine and concordant over the older formations. During the Pliocene the Zagros range was uplifted and thick conglomerates were accumulated. Many diapirs were active in orogenic and postorogenic time.

When salt outcrops and forms hills or mountains, the extrusion must be very recent and, in many cases, is probably still going on. Kuh-i-Namak in Dashtistan and Kuh-i-Shur are two spectacular examples of salt mountains towering 1,200 m above the level of the surrounding plain. Undoubtedly, the very dry climate of the area is responsible for the preservation of the salt mountains. It has also been proposed that the very rigid overburden, by preventing the formation of the peripheral sink, causes salt to flow until either the mother bed is depleted or a high enough mountain is formed so that its weight compensates the driving pressure difference. If the salt structures reaching 1,200 m above plain level are in isostatic equilibrium, the weight of the salt column should be equal to the weight of a column of sediments 1,200 m shorter, neglecting the original driving pressure that started salt deformation. For a salt density of 2.2 and sediment density of 2.55, the mother bed would be at a depth of about 7,500 m. On the other hand, even in very arid southern Iran, salt is removed by erosion and dissolution at such a rate that perfect equilibrium can probably never be reached. The situation might be further complicated by the plastic deformation of the salt masses under their own weight and resulting surface flows.

Surface Flow of Salt

Many diapirs are characterized by overhanging flanks. A generally accepted explanation for this feature is the growth of the salt plug through weakly consolidated sediments with density less than 2.2. Under these conditions the rising salt diapir can expand horizontally, because the uncompacted sediments offer limited resistance to the lateral spreading of the salt (Weller, 1959). If the diapir reaches the surface and rises above it, the salt is no longer supported by the encasing sediments and lateral spreading increases markedly.

The deformation is caused by lateral creep under the weight of overlying salt. The higher the salt relief, the faster the creep that causes the lateral spreading of salt. For such a situation to take place, the rate of salt extrusion must exceed the rate of salt removal by erosion and dissolution. This may well be the case for several salt diapirs in southern Iran, where, because of the limited rainfall, salt dissolution is minimal; however, in the past it has been true of other areas as well. Salt diapirs reaching the surface are known also in a few other areas characterized by arid climate, such as Spain and northern Algeria.

Figure 6 shows the Wienhausen salt diapir in northwestern Germany; it offers a good example of fossil surface flows. The diapir reached the surface in Upper Cretaceous time, and the structure was buried and preserved by the accumulation of Tertiary sediments.

In southern Iran many examples of surface flow of salt are known; they are usually called salt glaciers and can extend several kilometers away from the main salt mass. Harrison (1930) describes the Kuh-i-Siah Tak diapir and associated salt glacier in the following way:

> It forms a dome-shaped hill in a cirque bitten out of the northern edge of Kuh-i-Burkh. Between the salt and the precipitous limestone walls lies a flat-bottomed valley. The sediments follow the normal build of the anticline, and the circular valley between them and the terra-cotta-coloured salt plug is the zone of shattering which weathered away easily. The intrusion is about a mile and a half in diameter, and from its northern side extends a flat tongue-like sheet of salt and gypsum, 3 miles long and about 2 miles wide.
>
> The salt and gypsum of the plug proper is tinged red by overlying clay and sand debris. The

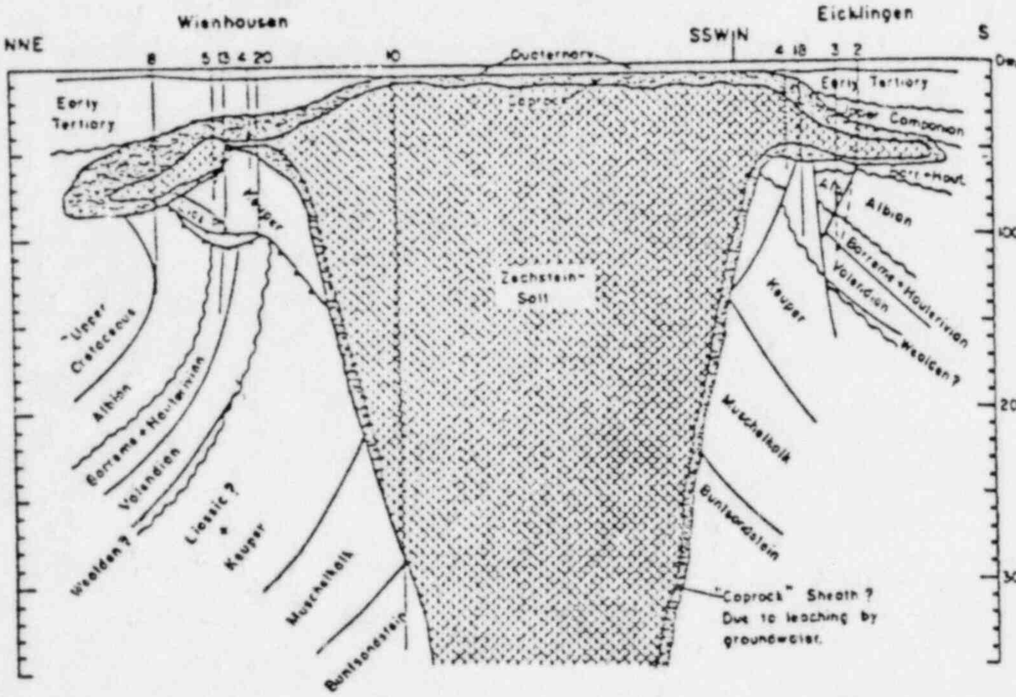

Figure 6. Wienhausen salt diapir, northwestern Germany. This cross section indicates that in Upper Cretaceous time the diapir reached the surface and formed a mountain of salt. The spreading at the surface was well advanced in upper Campanian time when sediments started to accumulate on the salt (*from* Schott, 1956, as adapted by Gussow, 1968).

slopes of this hill are in marked discordance with the slope of the saline sheet, marking, apparently, the junction between the limits of the plug and the 'glacier': this slopes outwards at about 3°. The edge of the sheet rises steeply from the alluvium with which it is in contact to a height of from 50 to 200 feet. The surface is irregular, and is seamed with crevasse-like gullies. Patches of epidotized basalt, brown siliceous shale, dark and striped limestones, and red sandstone rest on the main mass of the sheet, which is largely made up of salty gypsum, so that the white base is variegated by green, brown, black, and red.

The plug has cut through Eocene and Oligocene limestones on the northern side of a great anticline. Younger rocks are covered by alluvium. The disturbed contact zone has been removed by erosion. It was probably intruded after the main folding movements in Pliocene times, but this cannot be exactly determined.

A few kilometers away lies the salt diapir of Kuh-i-Gach. It forms a hill of salt more than 300 m higher than the plain. On the south side of the hill, salt spills over the plain, where it forms a tongue-like sheet about 5 km long. The diapir has a diameter of about 2,400 m. Once again, the surface of the salt shows a sharp discordance between the hill and the glacier. The margin of the glacier rises steeply from the alluvial plain to a height of 15 m or more. The salt sheet has a very gentle tilt outward from the diapir to the center of the plain. Figure 7 shows the Kuh-i-Gach salt diapir with its associated salt glacier. Figure 8 is Harrison's (1930) sketch map of the area showing the relationship of five salt diapirs, including the Kuh-i-Siah Tak and Kuh-i-Gach, with their salt glaciers. The important points are that

Figure 7. Kuh-i-Gach salt plug and associated salt glacier. (Redrawn *from* Harrison, 1930.)

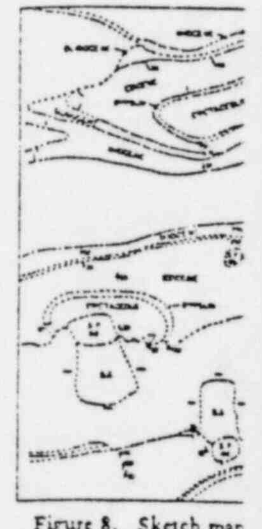

Figure 8. Sketch map
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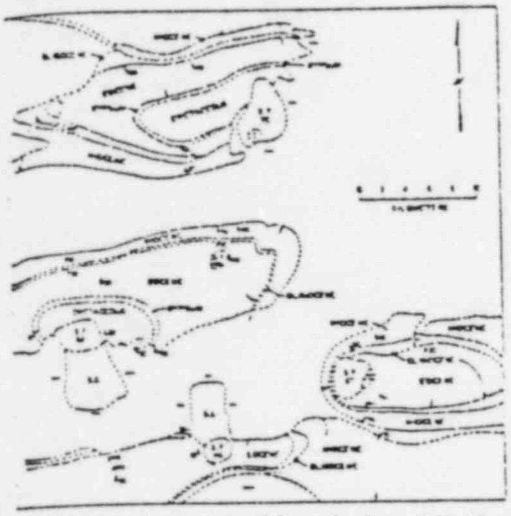

Figure 8. Sketch map of five salt plugs. S.P. 46 = Kuh-i-Siah Tak; S.P. 68 = Kuh-i-Gach; S.P. 67 = Kuh-i-Shur; S.P. 69 = Nuf-i-Rah; S.P. 70 = Kuh-i-Furdeh. S.G. = Salt "Glaciers"; C = Cretaceous; Gypsum = Infra-Nummulitic. (Redrawn *from* Harrison, 1930.)

the flow has occurred on a surface very close to horizontal and that large exotics have been carried along; therefore, the dominant mechanism of flowage must have been the plastic deformation of salt. The effect on salt glacier flowage of the scarce rainfall and associated dissolution and recrystallization is not known and might deserve investigation. Clearly, at least as illustrated in Figure 7, not enough stress is presently available to cause the flowage of the salt sheet. Therefore, it is necessary to interpret this and many other glaciers as residual features. At the time of the maximum rate of growth of the diapir, a high moutain of salt was formed which, under its own weight, spread over the plain. Later erosion has removed the salt mountain and most of the lateral flow. Present residual salt glaciers are greatly reduced in thickness, mostly by dissolution of halite, and consist now almost entirely of gypsum. The difference in slope of the salt surface at the boundary between diapir and glacier may be caused by the continued growth of the diapir.

Figure 8 is a map of several diapirs, including the Kuh-i-Shur (indicated as S.P. 67). The top of this salt mountain rises 1,200 m above plain level, but only the sumit is free from the enclosing sediments; therefore, no lateral spreading has occurred. Figure 9 shows a cross

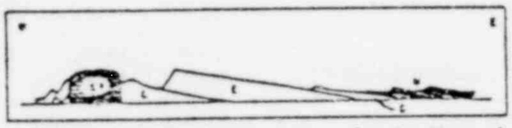

Figure 9. Diagrammatic section of Kuh-i-Shur salt plug (S.P. 67 in Fig. 8). Orientation of section is east-west. S.P. = salt plug; C = Cretaceous; E = Eocene; O = Oligocene; M = Miocene. (Redrawn *from* Harrison, 1930.)

section of the Kuh-i-Shur. The intrusion of this diapir is very recent, and probably salt is still rising. In the future, if the salt rises fast enough to compensate for salt removal, erosion will remove the sheath of sediments surrounding the salt plug, and a salt glacier will spread on the plain, probably toward the west. At the present, on the west side of the salt mountain, where the slope is very steep (Harrison, 1930)

> . . . the topography of the salt simulates an ice-fall and the characteristic restlessness of an Alpine glacier is also copied. Sharp cracks are heard every few minutes, and dislodged fragments come rattling down.

Where the salt surface is steep, the downslope motion of salt fragments can become an important mechanism. The resulting accumulation of salt detritus might undergo cementation to form a salt breccia. Figure 10 shows the Darbast salt diapir; the motion caused by gravity is evident. The term "flow of salt breccia" used by Kent (1958) to describe this feature supports the idea of downslope motion of salt fragments. Plastic flow is taking place in depth, unless the stress has already fallen below the yield limit of salt. A similar case of salt flow is shown in Figure 11; apparently the salt has spread over the Quaternary alluvial plain.

Essentially, the evolution of landforms on salt is a normal geomorphologic process. Salt, at the surface, fails by fracture and by flow; the two failure mechanisms contribute to the global action of mass movement. The driving energy of hillslope evolution is furnished by gravity. The ease of deformation and the solubility of salt cause a more rapid rate of evolution of landforms on salt than on other geologic materials. The action of rainfall on the evolution of slopes on salt in arid climates is probably significant.

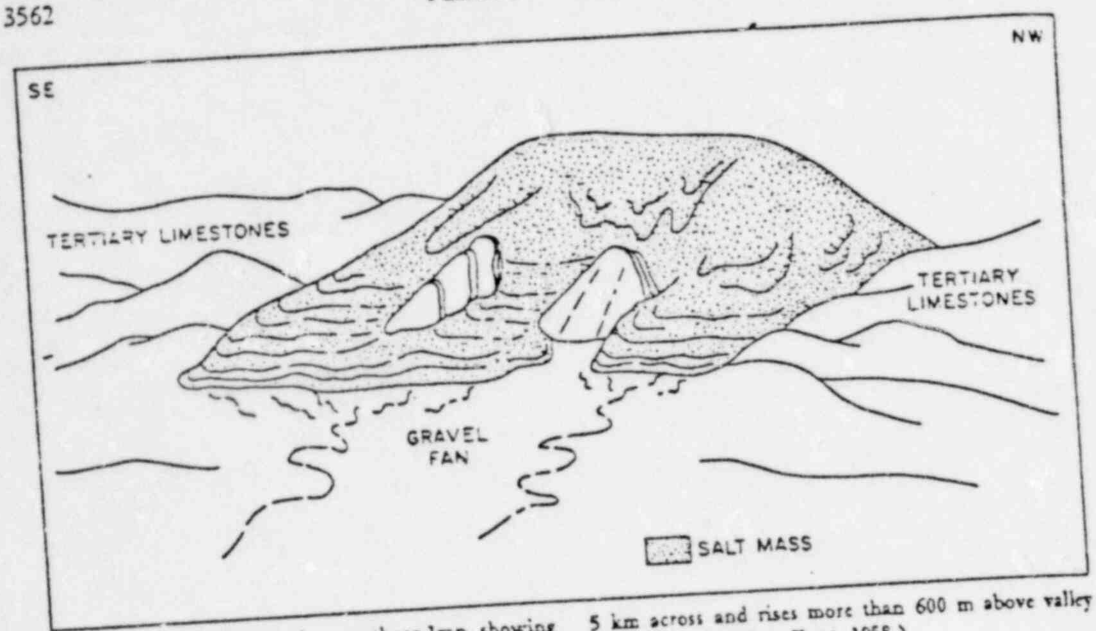

Figure 10. Darbast salt plug, southern Iran, showing scarps of Tertiary limestone covered by flows of salt breccia. Diapir with its outward flows measures about 5 km across and rises more than 600 m above valley level. (Redrawn *from* Kent, 1958.)

RATE OF SALT DEFORMATION

In the abundant literature on salt diapirism several estimates of rates of growth can be found. Most geologists believe that salt deformation is a slow process and that the actual rate of growth of salt diapirs is of the order of a few millimeters per year. The rate of salt movement is not the same in all phases of salt deformation; it is probably at a maximum in the late stage when diapirs are approaching or reaching the surface. In this phase the pressure difference due to the salt-sediment density contrast is close to its maximum, and the resistance offered by the overburden to the rising salt is very limited or even nil when salt is exposed at the surface. In the prepiercement stages of salt deformation, the pressure differences are much less and the resistance of the overburden is higher; therefore, even considering the higher average temperature of the salt, due to the greater depth, the rate of movement should be markedly less than the rate of growth of a well-developed diapir approaching the surface. Trusheim (1960) disagrees with this view, and reports Sannemann's conclusion that for the German Zechstein basin, the average rate of salt movement, on the geologic time scale, has been 0.3 mm per yr. Surprisingly enough Sannemann found that the flow rate of 0.3 mm per yr was roughly constant both in the prediapiric stage of salt pillow and salt anticline formation and in the dominantly vertical flow of the diapiric stage. It might be possible to reconcile these two opposing points of view,

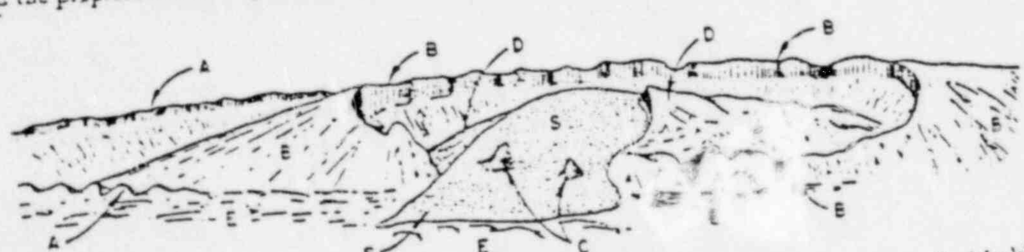

Figure 11. Field sketch of Kuh-i-Anguru salt plug and flow of salt spreading over the alluvial plain. A = scarp of Miocene limestone; B = scarp of Oligocene and Eocene limestone; C = peaks of B protruding through salt; D = hippuritic limestone; E = alluvial plain; S = salt mass. (Redrawn *from* DeBockh and others, 1929.)

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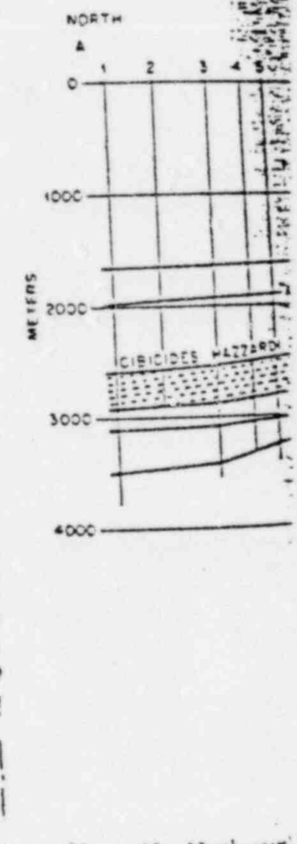


Figure 12. North–sout... Iowa salt diapir; no verti...

considering that the 0.3 mm per yr is a flow rate averaged over geologic time periods. In the stage of salt pillow formation, the physical conditions of the salt bed and the relations between salt and overburden are essentially uniform; therefore, a continuous, uniform flow of salt is probable. In the diapiric stage the situation is quite different; salt rises through progressively colder sediments that must be forcibly broken and pushed apart. The resistance that the overburden offers to the rising plug changes markedly as a function of the faulting. Therefore, an irregular, discontinuous movement seems the most logical mode of diapir growth.

Borchert and Muir (1964) conclude their review of the problem by stating that the usual rate of diapir growth is probably less than 2 mm per yr. At times the relations between salt and overlying sediments permit a reconstruction of the long and complex history of salt emplacement. Atwater and Forman (1959) describe several diapirs with a demonstrable history of salt emplacement extending over many millions of years. An example is furnished by the Iowa salt diapir, Louisiana, shown in Figure 12, for which several phases of uplift are known. It is interesting to note that the accumulation of oil is related to a fossil "high" caused by the Oligocene-Miocene uplift and not to the axis of the more recent uplift located about 1,500 m south. The displacement along the major fault is clearly caused by the youngest phase of uplift. This fault can be traced to within 450 m of the surface.

Borchert and Muir (1964) report Lotze's observation that, in Spain, rising diapirs of Keuper salt influenced the thickness of sediments accumulated during the Upper Cretaceous. A very limited thinning can be detected in the Cenomanian sediments, but it becomes quite apparent in the Turonian and very marked in the Senonian. Above the diapirs, the whole Upper Cretaceous succession is often less than a tenth as thick as in the sur-

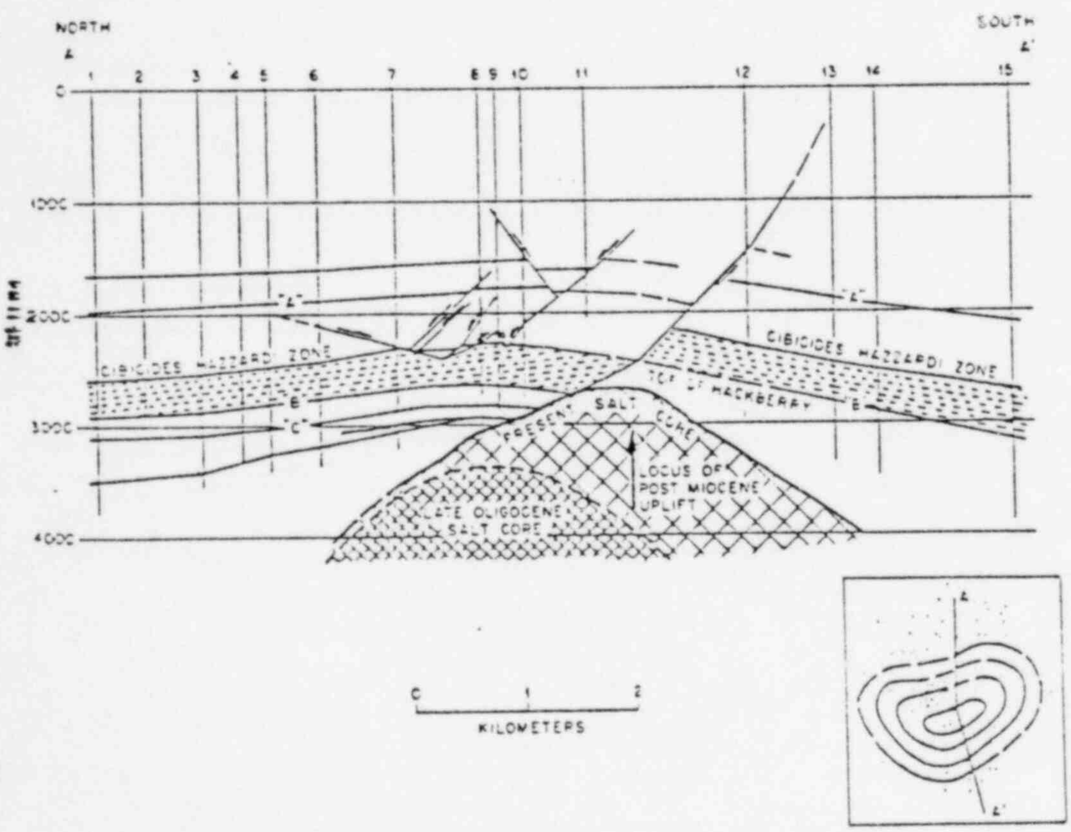


Figure 12. North–south structural cross section, Iowa salt diapir; no vertical exaggeration. (Redrawn *from* Atwater and Forman, 1959.)

rounding area. The only logical explanation is continuous growth during all this time period. A similar situation is probably occurring in several present basins, as discussed below in relation to the Sigsbee Knolls.

Considering the complexity of salt deformation and the many parameters that can actively modify the forces acting on the salt and the physical properties of the salt itself, it is no surprise that diapir growth is not a regular, uniform process. Balk (1949, 1953), Muehlberger (1959), and Kupfer (1963, 1968) have studied the internal structures of several salt domes in which mining operations have been conducted and concluded that salt advances in spines and lobes separated by shearing planes. The salt movement is probably jerky and irregular: possibly phases of diapir growth are separated by periods of stasis. The slow rate of growth has been questioned by some authors who maintain that the intrusion of salt diapirs in a geologic sense is a rapid, even a catastrophic process. Usually no quantitative definition of the terms rapid and catastrophic is given.

Thermal Considerations

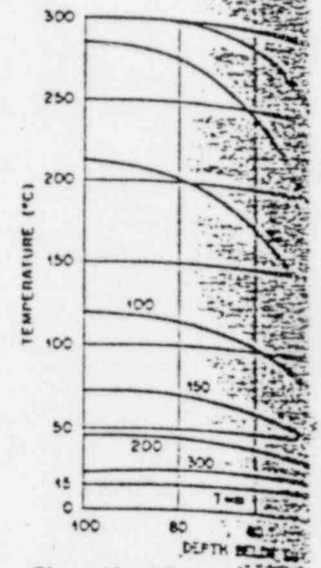
Gussow (1968) mentions the surface salt flows of southern Iran as proof that the salt reached the surface still hot. Therefore, Gussow's statement implies that salt moved so rapidly from the depth of about 9,000 m (where the supposedly critical temperature of 300° C might be reached) to the surface that no appreciable cooling had time to take place. It should be noticed that with such a high rate of intrusion the heat produced by internal friction would substantially affect the temperature of the salt. Even more revealing about the implied rate of salt deformation is the fact that the surface flows should have taken place before cooling of the salt below 300° C.

Therefore, the time available for the surface flow has to be assumed short or the salt could not remain hot. One of the salt flows described by Harrison (1930) is a sheetlike tongue extending for 5 km on an almost horizontal surface. For such a flow to take place before appreciable cooling, a very low equivalent viscosity of salt must be assumed. On the contrary, the available evidence indicates that the equivalent viscosity decreases smoothly with increasing temperature, and no sharp change in physical properties of salt exists in the temperature range of 0° to 750° C (Odé, 1968). The discussed disappearance of the work-hardening effect around 300° C has the result of keeping the rate of deformation constant under constant stress, but it does not reduce the equivalent viscosity. Serata and Gloyna 1959) have found that by increasing the temperature from 27° C to 410° C the rate of the transient creep is only increased by a factor of 90 and the rate of the steady state creep by a factor of 75. The conditions of the experiment were constant pressure of about 50 kg/cm² and no confining pressure. In the range between 600° and 750° C, Christy's (1956) experiments show that each 100° C-temperature decrease causes a 35-fold increase of the equivalent viscosity.

In this context is is acceptable to use the physical properties of salt determined by laboratory experiments, because the surface flow, as proposed by Gussow, would have occurred in a time span of comparable duration. Bradshaw (1970, written commun.) has calculated the time necessary for cooling to conditions of thermal equilibrium of a surface flow and of a salt diapir (Turner and Crowell, 1969). The salt temperature at the initial time is assumed to be 300° C throughout the salt mass, as it is required by Gussow's theory. Table 1 shows the physical properties of salt and sediments used in the calculation. Figure 13 shows the rate of cooling in two salt flows 50 and 100 m thick, respectively. To simplify the calculation, the salt flow is assumed to be of uniform thickness and infinite horizontal extension; in addition, no heat loss downward to the ground is assumed. Since the heat loss to the atmosphere should be controlling, the error introduced by the lack of downward heat flow is probably not greater than the intrinsic uncertainty of such calculations. It is clear that if we assume that the surface flow can only occur when the salt temperature is close to 300° C, the available time varies from several months for a flow 50 m or less in thickness, to several years for a flow of 100 m or

TABLE 1. PHYSICAL PROPERTIES OF SALT AND SEDIMENTS USED TO CALCULATE RATE OF COOLING

	Salt	Sediments
Density (g/cm³)	2.16	2.4
Thermal conductivity (cal/cm/sec/°C)	7.5×10^{-3}	4.14×10^{-3}
Heat capacity (cal/cm³/°C)	0.47	0.431
Diffusivity (cm²/sec)	0.016	0.0064



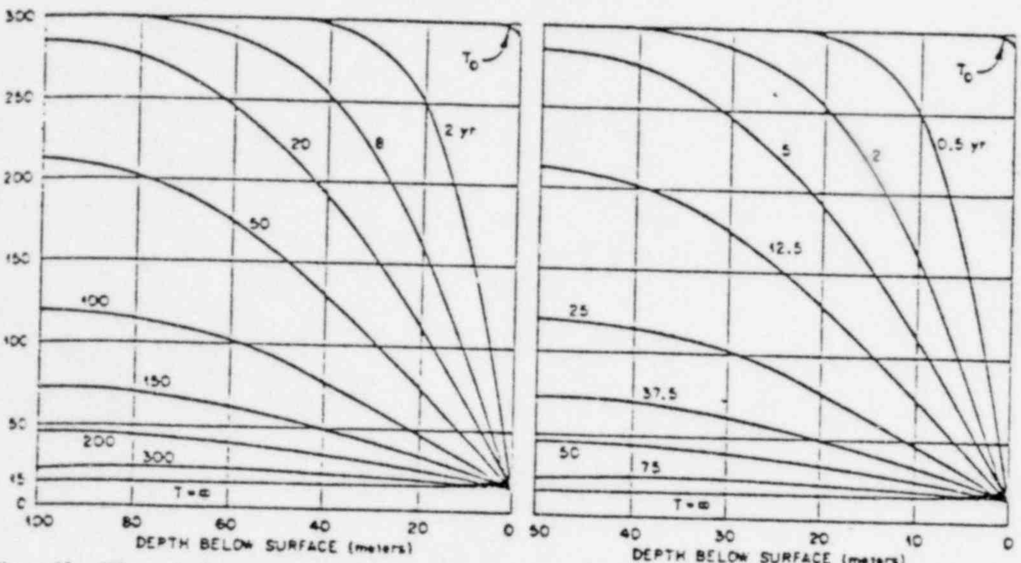


Figure 13. Theoretical temperature profiles of salt flows (100 m and 50 m thick, respectively) after various times of cooling.

more. For a 5-km-long salt glacier the rate of advance would average several meters per day.

On the other hand, a typical flow for ice glaciers is of the order of several meters per year; therefore, it would be necessary for the salt at 300° C to have an equivalent viscosity substantially lower than the equivalent viscosity of ice. Occasionally, ice glaciers undergo exceptionally rapid advances, but these surges are due to conditions of instability affecting the basal layer of the glacier, and not to the acceleration of the creep rate (Robin, 1969). Since the equivalent viscosity of ice is of the order of 10^{14} poises, 1 to 2 orders of magnitude lower than the equivalent viscosity of halite, and since even at 300° C the equivalent viscosity of halite is higher than 10^{15} poises, the inescapable conclusion is that the advance of salt flows at the rate of meters per day is physically impossible. It is thus confirmed that salt glaciers are due to normal geomorphologic processes and are not an indication of high salt temperature.

Figure 14 shows the rate of cooling of a salt column reaching the surface: the height is 9,000 m and the diameter is 3,000 m; therefore, the dimensions are comparable to those of some salt diapirs of the Gulf Coast or of southern Iran. To simplify the calculation, the surface temperature has been fixed at 15° C; temperature at the depth of 9,000 m is assumed to be 300° C. Additional boundary assumptions are that at 9,000 m from the center line of the plug, the temperature increases with depth (geothermal gradient 32° C/km) and no temperature variation is caused by the column of hot salt. In a time period of the order of 1 to 2×10^6 yrs, the salt structure can be considered to have reached thermal equilibrium. Bradshaw (1969, written commun.) has made additional calculations for a salt column with its top 150 m below the surface and diameter of 1,500 m, but the rate of cooling is not markedly different from the example of Figure 14.

Temperature measurements in salt diapirs indicate that the salt is usually at a somewhat higher temperature than the surrounding sediments at the same depth; however, this does not necessarily indicate a lack of thermal equilibrium, but simply reflects the high thermal conductivity of halite. However, in particular cases, the salt temperatures might be anomalous. The two main causes of the lack of thermal equilibrium could be either the residual heat from an originally and uniformly hot salt mass or the heat generated by internal friction in a presently rising salt plug. The distribution of temperatures inside salt structures might furnish some indication of the rate and mechanism of diapir emplacement.

The rapid intrusion model implies emplacement of salt at high temperature and termination of diapir growth when salt is depleted in the mother bed or when the peripheral sink

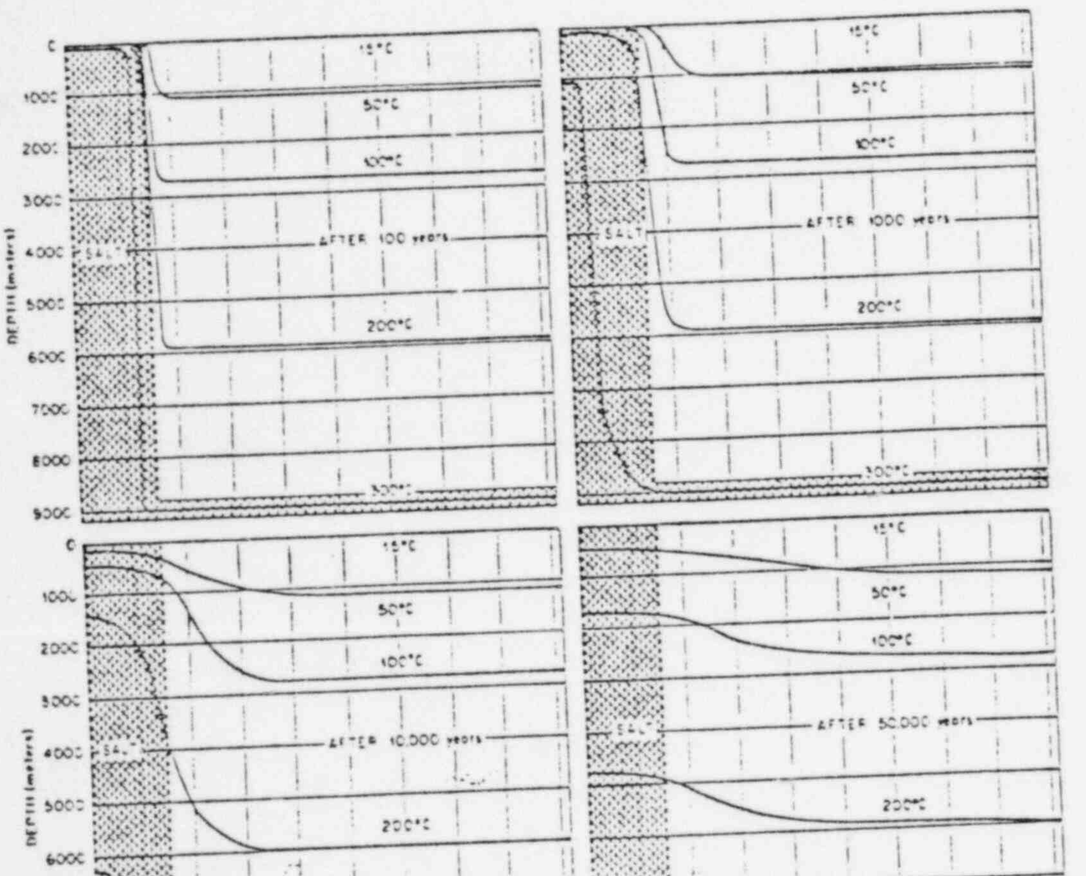


Figure 14. Theoretical temperature profiles after various times for the vicinity of salt diapir initially at 300° C.

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Shale Breccia

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cuts off the supply. The model would be supported if a diapir were found where thermal equilibrium has not been reached and where temperatures are generally high, with maximum values at the center line of the diapir. With the slow intrusion model, the salt is at all times in thermal equilibrium with the surrounding sediments. Locally, zones of abnormally high temperature, caused by internal friction, could be observed where salt is undergoing shearing. Therefore, the slow growth could be supported if abnormally high temperatures were measured close to the boundary of salt diapirs or in association with shearing zones. Selig and Wallick (1966) have calculated the heat generation at the boundary of a diapir growing at the rate of 0.25 mm per yr and found that it might affect the distribution of temperature in the salt. Since actual rates of growth can easily exceed 0.25 mm per yr, some temperature distribution related to friction heat generation should be recognizable. An interesting case is reported by Wynn (1965); an oil well drilled on the northeastern flank of the Jefferson Island dome (see Fig. 18 for location) had to be abandoned when a localized hot spot of 230° C was encountered at a depth of about 1,500 m.

Shale Breccia

One more voice in favor of the rapid intrusion theory belongs to Outmans (1966), who claims that "the rate of intrusion is explosive on a geological time scale once critical states of stress have been obtained." To support this statement, the faulting and fracturing evident in many shales pierced by salt diapirs are mentioned. However, fracturing is simply the sudden release of energy accumulated in strained rocks and does not give any indication of the rate of accumulation of the strain. The physical properties of shales depend on the amount of compaction they have undergone. Well-compacted shales are quite competent and deform primarily by fracturing (Kerr and Kopp, 1958). Shales that are weakly compacted, either because they have never been subjected to great pressure or because they did not lose the connate fluids, deform mostly by plastic flow. As a matter of fact, many examples of diapiric shales are known. Therefore, the fracturing of shales observed in connection with many salt diapirs is an indication of the state of compaction of the shale at the time of salt emplacement and not of the rate of intrusion of the diapir.

Sigsbee Knolls

In recent years many diapiric structures have been discovered under the bottom of the sea. Salt diapirs exist not only on the continental shelf in fairly shallow water, as in the northern Gulf of Mexico where by 1968 close to 80 diapirs had been drilled for oil, but also in deep sea basins, such as the central part of the Gulf of Mexico. In August 1968 Challenger Knoll, one of the Sigsbee Knolls, was drilled in about 3,600 m of water, and it was proven that these small hills are the sea bottom expression of salt diapirs (Ewing and others, 1969). The Sigsbee Knolls are located in the very flat Sigsbee Abyssal Plain, which occupies the deepest part of the Gulf of Mexico.

All the observed data strongly support the interpretation of a diapir growing at a rate similar to the accumulation of sediments on the abyssal plain (Ewing and Ewing, 1962; Burk and others, 1969). Figure 15 shows the relation of the salt diapir to the surrounding sediments. The abyssal plain sediments are mainly turbidity current deposits with a pelagic component that was less than 25 percent in the upper Pleistocene and Holocene. In the lower Pleistocene and Pliocene turbidites made up a little more than half of the total sedimentation; in the upper Miocene turbidites were again predominant. On the other hand, all sediments cored on Challenger Knoll are pelagic and the drilling was stopped at a depth of 144 m below the sea floor in the cap rock. The cap rock is overlain by sediments of upper Miocene age. The lack of turbidites on the Challenger Knoll proves that this diapir has caused a topographic relief sufficient to prevent turbidite deposition, at least since upper Miocene time. The thinning of sediments on the flanks of the knoll, as revealed by the seismic reflection profiles, strongly suggests growth during sedimentation. Of course, some of the thinning is caused by differential compaction between the thick turbidites and their pelagic equivalent on the knoll. However, downbuilding cannot be the main process at work or the knolls would be rapidly buried under the accumulating sediments. Another important piece of information furnished by the drilling of Challenger Knoll is that cap rock can be formed under the floor of the

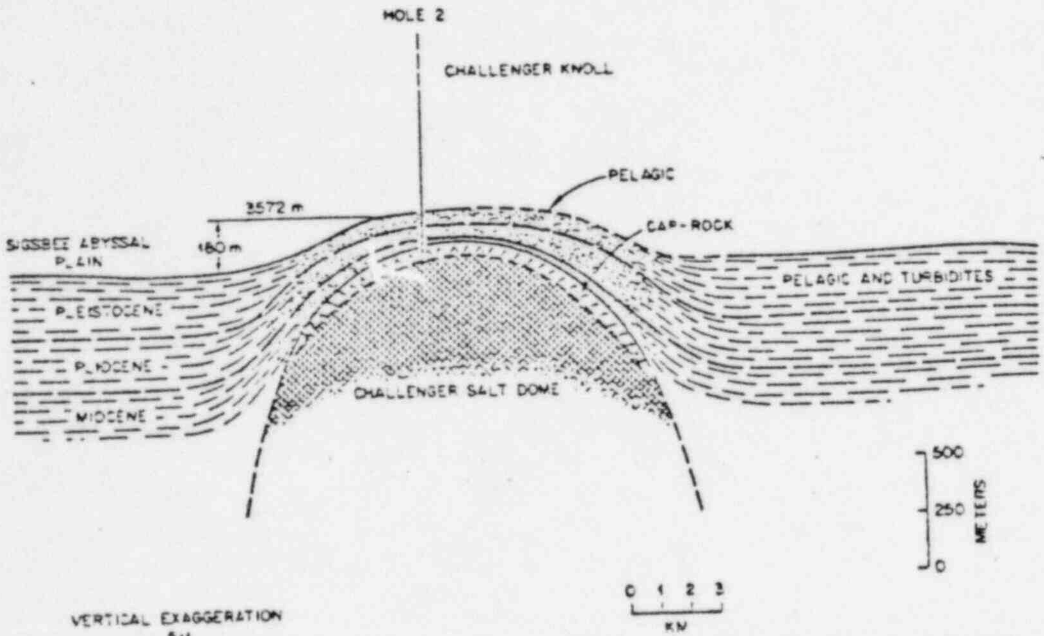

Figure 15. Structural cross section through Challenger Knoll. (Redrawn *from* Ewing and others, 1969.)

ocean. In this case, the dissolution of salt can only be caused by percolating sea water; clearly this process limits the uplift of the strata above the rising diapir.

Near the crest of one of the Sigsbee Knolls, Bryant and Pyle (1965) have collected a core 5.5 m long, which contains indurated sediments of middle Miocene age. The Miocene sediment is a calcilutite indicating that sedimentation was prevailing pelagic. The compaction indicates that in the past the middle Miocene sediments have been covered by younger deposits. The present situation can only be explained by erosion or slumping of younger sediments off the sides of the knoll. These examples of reduced accumulation of sediments on top of a growing d... ir help to explain many puzzling relations between salt structures and surrounding sediments. For example, Day dome (Madison County, Texas), described by Bornhauser (1969), is surrounded by sediments showing no appreciable upturn. Figure 16 shows a cross section through this dome down to a depth of about 3,000 m. Clearly no piercement occurred through the undisturbed strata, even if some piercement must have occurred through strata now buried at greater depth. The logical explanation is that the missing sediments were never deposited over the salt diapir or were continuously removed by slumping and submarine erosion. This explanation requires that the diapir had a positive topographic expression for all the period of no accumulation over its top. Therefore, the rate of growth of the diapir must have been of the same order of magnitude as the rate of sedimentation.

Caprock Formation

Salt diapirs with a thick caprock formation offer conclusive proof that diapir growth is a slow process. Many diapirs are known with a caprock formation exceeding 300 m in thickness (Murray, 1961, 1966). Naturally, the volume of salt that has to be dissolved by ground water to accumulate a certain thickness of cap rock is a function of the amount of insoluble impurities contained in the salt. Kupfer (1963) has reviewed the problem of the composition of Gulf Coast salt and concluded that the average anhydrite content is under 3 percent. In the salt structures of the Gulf Coast, anhydrite constitutes 99 percent of all insoluble impurities.

Occasionally, cases of markedly higher anhydrite content have been reported. For example, Hanna (1934) has dissolved specimens of salt from 90 m below the caprock contact in the Hockley dome, Harris County, Texas (see Fig. 18 for location), and found the insoluble

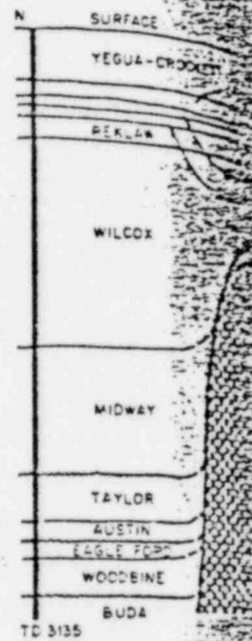

Figure 16. North-... through Day dome, Ma...

residue to be 15.3 perce... anhydrite content at the ... m of salt should have be... ulate the 270-m-thick ... For many other diapirs, ... is closer to Kupfer's v... of dissolved salt shoul... thousand meters. For ... (1969) has calculated th... have been dissolved fro... County, Texas, for a ... 6,000 m.

If the emplacement ... catastrophic affair, the ... time of emplacement sh... sands of meters higher ... of the caprock formatio... impossible, the only po... growth of the diapir du... salt. Subsidence over a d... overlying strata collapse ... the dissolved salt. This ... when no salt uplift is o... rate of salt dissolution ex... growth. However, the ... sidence indicated by ... cannot account for the ... missing salt.

Clearly the rate of

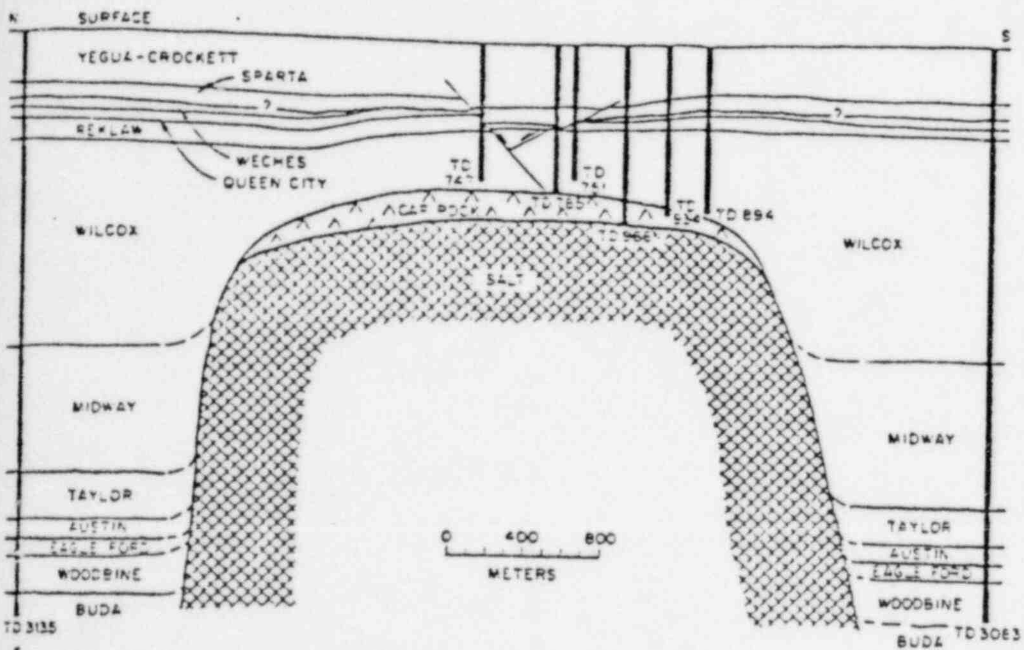

Figure 16. North–south structural cross section through Day dome, Madison County, Texas; no vertical exaggeration. TD = total depth of wells in meters. (Redrawn *from* Bornhauser, 1969.)

...sidue to be 15.3 percent. If this is the average anhydrite content at the Hockley dome, 1,800 ...of salt should have been dissolved to accumulate the 270-m-thick caprock formation. For many other diapirs, the anhydrite content ...closer to Kupfer's value, and the thickness of dissolved salt should have been several thousand meters. For example, Bornhauser (1969) has calculated that about 45 km^3 of salt have been dissolved from Day dome, Madison County, Texas, for a thickness of 5,000 to ...000 m.

If the emplacement of salt diapirs were a catastrophic affair, the top of the salt at the time of emplacement should have been thousands of meters higher than the present top of the caprock formation. Since this is clearly impossible, the only possibility is continuous growth of the diapir during dissolution of the ... Subsidence over a diapir occurs when the overlying strata collapse into the space left by ...dissolved salt. This is possible in periods when no salt uplift is occurring or when the rate of salt dissolution exceeds the rate of diapir growth. However, the magnitude of total subsidence indicated by the geologic relations ...not account for the thousands of meters of ...ing salt.

Clearly the rate of salt dissolution is a function of the volume of ground water coming in contact with the salt per unit of time. However, no quantitative correlations between dissolution rates of salt and hydrologic properties of the surrounding formations have been found in the literature.

Evolution of Rim Synclines

Another way to obtain information about the evolution of salt structures is to study the rim synclines. The rim syncline forms simultaneously with the accumulation of salt in the area of uplift; it results from the downwarping of the overlying strata into the space vacated by the salt flowing into the growing structure. In the Gulf Coast area few wells reach depths at which useful data on the evolution of rim synclines can be obtained. In addition, wells are normally located on structural "highs" where accumulation of oil and gas is possible. Therefore, most data on rim synclines are furnished by seismic reflection profiles.

In Germany, where the mother bed is much closer to the surface, rim synclines are more accessible and their evolution is better known. Trusheim (1960) and Sannemann (1968) have described the shift of the axis of the peripheral sink toward the axis of uplift. The variations in thickness of the strata are caused by differ-

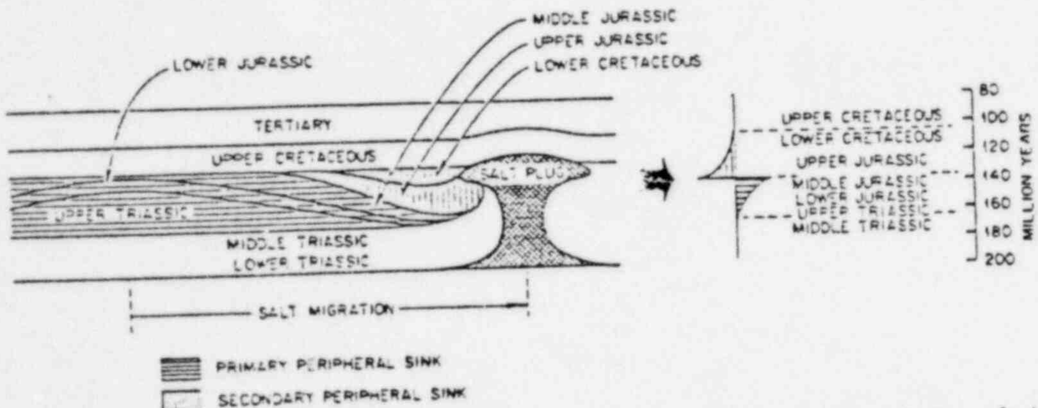

Figure 17. Diagram showing idealized relation between a salt diapir and the peripheral sink. Notice migration of the axis of the rim syncline through geologic time and resulting pseudoanticline with axis located on the site of the primary sink. Rate of salt migration can be estimated. (Originally designed by Sannemann; redrawn *from* Trusheim, 1960.)

ential accumulation between rising and subsiding areas. Figure 17 shows the idealized cross section of a salt diapir and associated rim syncline. At the end of the process of diapiric intrusion, a structural inversion is completed. The area of the primary subsidence, formed when flowage of salt was in the initial stage, becomes structurally high (see also Fig. 4). The oil field Düste in Lower Saxony is located in a pseudoanticline of this kind. At the time of piercement of the overburden, salt is squeezed into the diapir and the anticline that supplies the salt collapses under the weight of overlying sediments. At the surface there is a central uplift surrounded by a sunken area. Sedimentary processes result in reduced accumulation on the uplift and an increase of accumulation in the sink, thereby intensifying the pressure difference responsible for the flowage of salt (Murray, 1961).

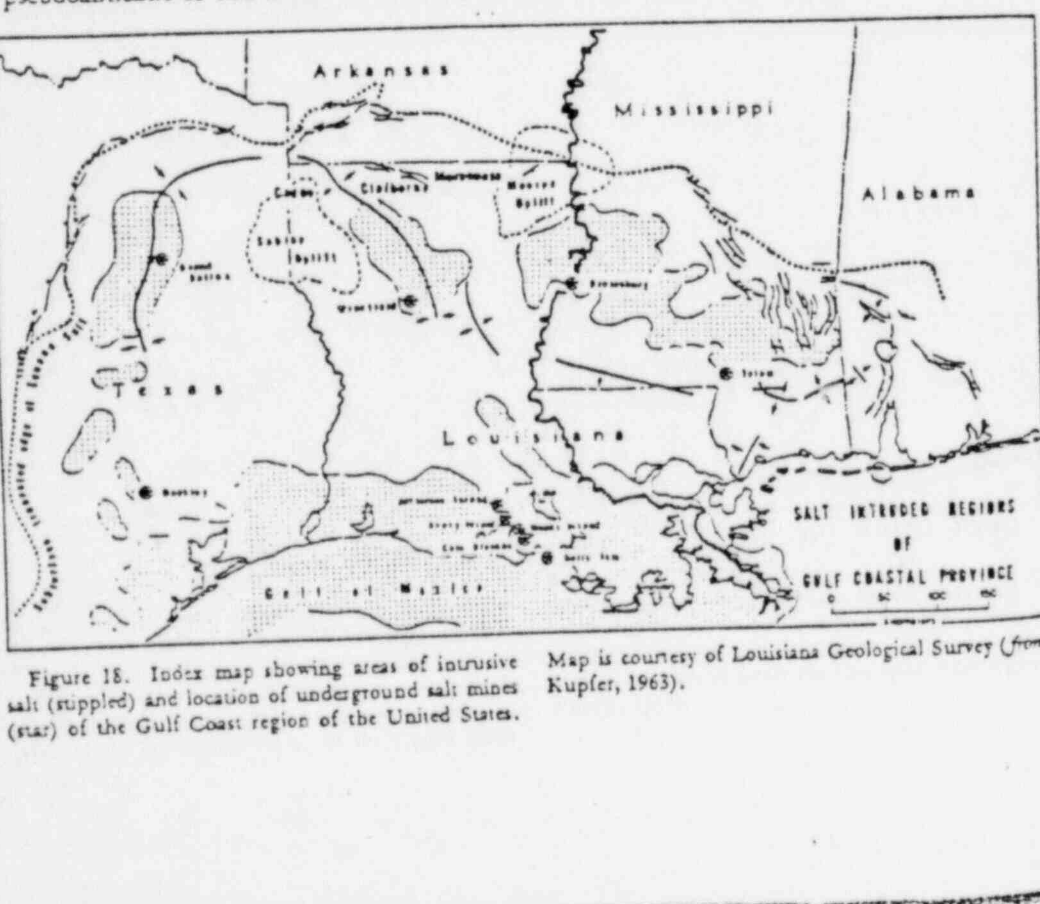

Figure 18. Index map showing areas of intrusive salt (stippled) and location of underground salt mines (star) of the Gulf Coast region of the United States. Map is courtesy of Louisiana Geological Survey (*from* Kupfer, 1963).

Figure 18 shows
Islands in southern
example of diapin
Five Islands' region
Jefferson Island
Belle Isle at the
steeply and thicken
Apparently, the syncline
salt, accumulated in
squeezed into the
(Bates and others,
Madison County,
which there is good
anticline that supplied
Bornhauser (1969)
volume of salt intruded
km³, of which about
form the cap rock.
the volume of the
is located. The migration
syncline through geologic
collapse of salt anticline
of intrusion of salt
different from the
processes.

Present Movements

Finally, there are
actual salt movements
the growth of salt diapirs.
ments have been observed
located in salt diapirs or
of shallow salt diapirs.
the interpretation of
obtained in salt mines
of the mined cavities
occasionally very rapid,
observed uplift, the
of the surrounding area
of the sediments should
a few cases of salt movement
it is likely that many
revealed if the appropriate
conducted. For deep
of movements would be
difficult because of the
of salt uplift. Microseismic
furnish a valuable tool
growth of salt diapirs,
no observations of this
have been reported in the

Lotze (1957) mentions
of 1 to 2 mm per yr has
stocks of the Caspian
(1960) reports Teichmuller

Figure 18 shows the location of the Five Islands in southern Louisiana, which gives an example of diapirs located in a syncline. The Five Islands' regional syncline extends from Jefferson Island at the northwest to beyond Belle Isle at the southeast. Sediments dip steeply and thicken into this regional trough. Apparently, the syncline was formed when the salt, accumulated in a long salt anticline, was squeezed into the various diapirs of the area (Bates and others, 1959). The Day dome, Madison County, Texas, is another case for which there is good evidence of a former salt anticline that supplied salt to the diapir. Bornhauser (1969) has estimated the total volume of salt intruded in the day dome as 90 km^3, of which about half has been dissolved to form the cap rock. This value agrees well with the volume of the trough where the Day dome is located. The migration of the axis of the rim syncline through geologic time and the slow collapse of salt anticlines prove that the rate of intrusion of salt diapirs is not significantly different from the rate of other geologic processes.

Present Movements

Finally, there are several observations of actual salt movements that can be related to the growth of salt diapirs. The reported movements have been observed either in mines located in salt diapirs or at the surface on top of shallow salt diapirs. Caution is necessary in the interpretation of data on deformation obtained in salt mines because of the closure of the mined cavities that always occurs, occasionally very rapidly. In the instances of observed uplift, the possibility of subsidence of the surrounding area because of compaction of the sediments should be analyzed. However, a few cases of salt movement seem certain, and it is likely that many more instances would be revealed if the appropriate measurements were conducted. For deep diapirs the observation of movements would be expected to be more difficult because of the probable slower rate of salt uplift. Microseismic data might well furnish a valuable tool for investigating the growth of salt diapirs, especially in depth, but no observations of this nature are known to have been reported in the literature.

Lotze (1957) mentions that a relative uplift of 1 to 2 mm per yr has been measured on salt rocks of the Caspian depression. Trusheim (1960) reports Teichmuller's conclusion that the rise of the salt stock of Segeberg, in Holstein, northern Germany, has been about 2 mm per yr in the last 20,000 yrs. From observations by Lees and Falcon, Trusheim (1960) has calculated a rate of salt movement of 2.4 mm per yr in salt structures located in Iraq. Sheets (1947) reports that active movement has been measured at Hoskins Mound, Brazoria County, Texas. An area of 100 acres located in the central part of the diapir has apparently risen a maximum of 18 cm in a 23-yr period (1922 to 1945); the resulting rate of uplift at the surface is about 8 mm per yr, which because of the known subsidence of the surrounding area, is likely to be an overestimate. However, it could be the beginning of a salt spine such as those present at Anse La Butte, Jefferson Island, and Belle Isle in Louisiana.

Muehlberger and Clabaugh (1968) report that in 1937 part of the mine located in Winnfield salt dome, northwestern Louisiana, was accidentally flooded, causing a water-etched line. After 27 yrs, the etched line was no longer horizontal, but showed a deformation amounting to several centimeters.

In a railroad cut on the northern slope of Jefferson Island, brackish water fossils were found in loose sand, 6 to 9 m above sea level (Balk, 1953; Vaughan, 1925). The fossils were identified and found to be proably of late Pleistocene or early Holocene age. If more accurate dating should confirm the age of these fossils, the logical explanation would be that at the beginning of the Holocene, 11,000 yrs B.P., the sand was accumulated in a brackish water marsh located at sea level; from this it would follow that the deposit has been uplifted to the present level during this span of time. Considering that 11,000 yrs ago sea level was about 30 m below the present level (Fairbridge, 1960), the uplift might be 30 to 40 m in a time span of 10,000 to 15,000 yrs, which gives a rate of growth of 2 to 4 mm per yr. It is worth noticing that only part of the salt core shows signs of recent rising at Jefferson Island. The major part of the diapir terminates in a flat surface at a depth of about 250 m. On the southeastern edge of the diapir a spine rises to the average elevation of the surface in the area. However, no salt is exposed at the surface, as about 20 m of sediments overlying the salt spine were arched to form the hill called Jefferson Island (Wharton, 1953).

Vaughan (1925) reports also that near Shaft Hill on top of the Belle Isle diapir, one of

Louisiana's Five Islands, a conglomerate bed with strike N. 75° E. and dip 23° NW. is exposed. The fossils in the conglomerate are all species represented on the Gulf Coast today. It is clear that since accumulation, this conglomerate has been tilted to an angle of 23°. In this case the data are insufficient to calculate the rate of uplift, but the evidence of recent movement is inescapable.

Finally, there is the observation that of the thousands of salt structures known throughout the world, none has ever been observed to undergo the rapid growth postulated by a few authors. Since all stages of development of salt structures can be observed, the only possible conclusion is that salt diapirism is regularly occurring whenever conditions are appropriate, but only accurate measurements or geologic observations can provide evidence of the slow rate of movement.

CONCLUSIONS

In relation to the problem of disposal of radioactive waste, the most important aspect of salt deformation is the rate of the process in its various stages. If the time necessary for an unacceptable deformation of the disposal formation should exceed the time required for decay of ^{239}Pu to nonhazardous levels (a few hundreds of thousands of years), the whole problem of the plastic deformation of salt would have little relevance to the disposal of radioactive waste.

From this review of the tectonics of salt formations, it seems fairly well proven that the risk of containment failure because of the plastic deformation of the salt is negligible if the waste repository is located in a salt formation that meets the following conditions.

1. It should be a bedded salt formation showing no evidence of plastic deformation in the recent geologic past, and be located in a tectonically stable area.

2. The salt beds should be close to horizontal, and the surface relief should be minimal to insure a very limited differential loading.

3. The thickness of the salt beds should be adequate to furnish safe containment but less than the 300 to 400 m necessary to produce sizable salt structures.

4. The salt beds should not be located at great depth where the plasticity of salt is increased by the high ambient temperature. However, this is only a theoretical problem, because the maximum depth is limited much more drastically by the required stability of mined cavities than by the plasticity of the salt formation. On the other hand, a depth of at least 300 to 400 m seems desirable to remove the waste from geologic processes active at or near the surface.

Although salt diapirs certainly exist for which no future salt uplift is possible because of depletion of salt in the source area, nevertheless the demonstration of the safety of disposal in a salt diapir would require very extensive geologic investigations. In addition to the structural problems, diapirs would present much more serious hydrologic problems, because of the complexity of ground water circulation in the adjacent fracture zone and because of the possibility of temporary permeability of the salt mass in correspondence with shearing zones.

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MANIK TALWANI
OLAV ELDHOLM

Continental ...
A Geophysical ...

ABSTRACT

Geophysical inv... gravity, magnetic, ... reflection and refraction ... made aboard R/V ... margin off Norway. ... data in the area, maps ... free-air gravity, magnetic ... sity, seismic refraction ... thickness and thickness ... have been constructed. ... sented as profiles across the ...

The Vøring Plateau is ... escarpment; the basement ... seaward side and deep ... A similar marginal ... Shetland, exists farther ... ments mark the site of ... of the Norwegian Sea. ... ments overlie a basement ... floor spreading. Landward ... of sediments that may ... overlies a continental ... quiet zone on the landward ... ment is attributed to the ... of the basement.

A nearly continuous ... and magnetic anomalies ... ward of the edge of the ... primarily to intrabasement ... in rocks that are probably ... It extends from northern ... Lofoten–Vesterålen islands ...

The continental margin ... an epicontinental sea ... North Sea in which a large ... tation kept pace with sub... non which perhaps started ... The thickness of pre-Ce... ceeds 6 km in some are... minimum over the belt ...